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Final Report: Emergent Forest dynamics and Natural Flood Management

Land, Soil and Coast Programme and Groundwater Programme

Internal Report OR/17/014

BRITISH GEOLOGICAL SURVEY

LAND, SOIL AND COAST PROGRAMME AND GROUNDWATER PROGRAMME

INTERNAL REPORT OR/17/014

Final Report: Emergent Forest dynamics and Natural Flood Management

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SW corner 999999,999999
Centre point 999999,999999
NE corner 999999,999999

Map

Sheet 999, 1:99 000 scale, Map name

Front cover

The pinewood forest in Rothiemurchus, Cairngorms.

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Foreword

As part of the British Geological Survey Land, Soil and Coast Program and Groundwater Program and funding from the Scottish Forestry Trust, this report describes a two year investigation of the Rothiemurchus Old Pinewood area in the Cairngorms, focusing on a 40 year old Scots pine plantation and an adjacent ~300 year old Scots pine area.

Acknowledgements

We acknowledge that staff time and lab analysis is funded by the British Geological Survey from Land, Soil and Coast, the Groundwater Science Ppogramme. We are grateful for the funding of fieldwork and equipment by the Scottish Forestry Trust, which enables this project to be carried-out. We also acknowledge the support of the Forestry Commission and their permission to allow us to work in Rothiemurchus Forest.

The authors would like to thank Mr Piers Voysey for his time providing background information and views of the Rothiemuchus forest and to Mr Colin Leslie in the Forestry Commission, who gave helpful information and access to Rothiemurchus Forest.

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Executive summary

The study area is within the Rothiemuchus Forest approximately 2 km south west of Loch Morlich, near Aviemore in the Cairngorms. The main aim of this study was to improve the understanding of forest hydrology to contribute to a better management of forests (planting and conservation) in view of mitigating flood risk. To do this it was proposed to investigate water flow and storage and absence/presence of springs within two adjacent sites within the Rothiemurchus Forest. These two sites were plantation Scots pine (*Pinus sylvestris*): planted in 1971 and Old Forest Scots pine, initially planted or left to regenerate in 1750. The topography is comprised of undulating moraine deposits, creating hill crests and moraine depressions overlying the Ardveriki Till Formation on micaceous psammite (sandstone) bedrock. Soils are ferric podzols with peat layers.

Between the two sites it was observed that:

- No flowing springs or seepages were found in the Scots pine plantation area and four flowing springs were found in the Old Forest site.
- Peat was significantly thinner in moraine depressions and thinnest on moraine crests.
- The density of trees in the Old Forest was significantly higher in the more freely draining moraine soils than the mire depressions between the moraine slopes.
- It was difficult to quantify the number of standing plantation trees within the moraine topography, but field surveys observed uprooted or windblown trees (blown down by wind) in particularly in moraine depressions.
- The occurrence of the Ardveriki Till Formation below the more permeable morainic deposits suggests that perched water tables occur in the boggy depressions in the moraine topography, because the less permeable layer of Till prevents water drainage. Also within the moraine slopes fine compacted ‘lenses’ of sediments occur from glacial retreat and ice melt.

To further investigate the possible reasons for the above observations, the two sites were instrumented with soil water sensors and rain gauges. Soil and vegetation depth was investigated by auger cores and the use of an avalanche pole. Field saturated hydraulic conductivity was also measured using a systematic random design.

It was observed that the Old Forest site had significantly thicker soils, and understory cover than the Plantation site. Cumulative ground-level rainfall recorded in the Plantation site was 15% less than the Old Forest, suggesting that the dense plantation canopy intercepted rainfall, causing water to be stored and evaporated from the plantation canopy, reducing the quantity of water entering the soil. Field saturated hydraulic conductivity (*Kfs*) measured by a Guelph constant head well permeameter was used to estimate the soil’s ability to transmit (infiltrate) water. In the Plantation site median *Kfs* was 0.13 cm/min with a narrow range of values (0.002 to 2.4 cm/min), whilst median *Kfs* measured in the Old Forest was 0.057 cm/min (wider range 0.00004 cm/min to 4.8 cm/min). In the Old Forest, *Kfs* values were significantly greater within vegetation/soil mounds, than depressions, whereas in the Plantation site there was no significant difference of *Kfs* between depressions and soil/vegetation mounds, where drainage lines were a dominant factor within the slope topography. A topographic study of the both sites showed that the dominant water flows were downslope towards bog areas in moraine depressions. Soil water contents in the Plantation responded to rainfall events and drained relatively quickly corroborating *Kfs* measurements, whereas the Old Forest demonstrated diverse responses to rainfall events. The majority of soil moisture sensors did not respond to rainfall, but were buffered by vegetation cover, although responses to rainfall were rapid in areas of sandy gravels.

In conclusion, the Plantation tends to have drier moraine slopes (to 0.4m depths), not conducive to spring development, because i) the dense canopy intercepts a component of rainfall, ii)_there is

significantly less understory vegetation and thinner soil, leading to rapid infiltration through the permeable moraine substrate, which drains towards moraine depressions. The reasons for significantly thinner soils in the Plantation site could be due to a number of combined reasons, such as: 1) During the implementation of drainage and tree planting, the peat soils became disturbed and vulnerable to erosion by the increased amount of water flow through the newly installed drainage. 2) The loss of shrub canopy through the process of tree planting exposes the soil to erosion and as the plantation grows the loss of understory biodiversity, causes the soils to become eroded particularly under high rainfall. 3) With increased infiltration rates, the soils are more highly drained, causing the water table to lower. The peat then becomes drier and oxidization of the peat occurs, lowering the depth of peat. Further research is needed to understand such significant differences.

The significantly deeper vegetation understory and soil thickness developed in the Old Forest provides greater diversity of *Kfs* allowing infiltration of rainfall and water storage. Thicker forest soils store more water, because they are more aerated than mire peats (Kurbatov, 1968) and therefore act as a "sponge" to store rainfall. Spring development is dependent on impermeable substrate layers in moraine deposits, such as those occurring in the Cairngorms. However, if these layers are thin, they can be easily broken by ploughing. In the Old Forest, the dense understory of blaeberry, bearberry, heather and sphagnum may protect these impermeable layers, where water accumulates as springs/seepages. Even though *Kfs* are significantly lower in the depressions than the vegetated mounds in the Old Forest, water will continue to flow towards springs under gravity, creating a constant water supply for spring flows.

This study was unable to find evidence that the Old Forests interact with the soil and shallow geology leading to the occurrence of springs. However, as this study is the first of its kind to investigate spring development in relationship to forests in Scotland, it provides the basis for further research. Future studies should consider how soils form through forest interaction with the surrounding geology (parent material). Where the geology or soil parent material is relatively impermeable, perched water tables are likely to occur, leading to local spring development.

1 Introduction

1.1 THE PROPOSED INVESTIGATION

The main aim of the project is to improve our understanding of forest hydrology to contribute to better management of forests (planting/conservation) to mitigate flood risk. To do this it was proposed to investigate water flow and storage at three sites with differing vegetation: heathland/pastureland, mature scots pine plantation and ancient Caledonian forest.

Work done by BGS and the University of Dundee in the Scottish Borders has shown that the presence of established deciduous woodland has a significantly greater impact than younger coniferous plantations in increasing soil permeability, enabling heavy rainfall infiltrating the ground and reducing surface runoff, irrespective of soil type (Archer et al., 2013). The majority of research based on natural flood management (NFM) and forest establishment has been undertaken in newly planted woodlands or plantations (Marshall et al., 2014), where it is not possible to investigate the "maximum potential" which the forest may attain to mitigate flood events, considering that many tree species live for more than 100 years. A preliminary survey of infiltration rates in an ancient Caledonian forest (*Pinus sylvestris*) considered to have existed over 4000 years), observed infiltration in relatively deep soil layers 100 times greater in comparison to a 48 year old Scots pine (*Pinus sylvestris*) plantation, and that infiltration rates under a newly planted Scots forest was even lower than pastureland (Archer et al., 2014). This study continues such research, by focusing on the dynamic, below-ground processes of long-term root dynamics (growth and dieback), which alter below-ground water pathways and may even decouple rainfall that flows through soils to streams, as has been suggested by recent evidence (Phillips, 2010). Loss of forest cover has been attributed to reductions in discharges to springs and seepages (Valdiya and Bartarya, 1989).

The study will test two hypotheses:

1. *as these forests develop, the root system creates macropores and increases organic matter concentrations within the soil/root layer, optimising on the one hand to store water in the more organic soil and the other hand to allow water to flow via old root channels*
2. *springs develop within and around mature forests because their rooting systems interact with the soils in such a way as to form permanent and/or ephemeral perched water tables*.

The project compares the flood mitigation potential of forest plantation, ancient forest and heathland using in-situ permeability measurements at different soil depths and investigating the frequency of springs within the three sites.

This pilot study will also examine past climate and local disturbance to deepen our understanding of forest ecosystem resilience, by taking soil cores and carrying out carbon dating and analysing polycyclic aromatic hydrocarbons (PAH) to test for disturbance (as described by Vane *et al*.. 2013).

1.2 FIELD WORK

Following the project proposal, the fieldwork was divided into four parts:

1. Site evaluation
2. Survey of area and spring locations
3. In-situ hydraulic conductivity measurements
4. Quantifying local past disturbance of the Rothiemurchus Forest

The site evaluation and spring survey created the foundations for the project. Through this process it was concluded to modify the original proposal and focus on understanding the undulating moraine terrain in terms of spring development within adjacent plantation and Old Forest, using a re-formulated context shown in Figure 1. The proposed conceptual model focuses on UK forestry in glaciated landscapes and removed the suggested heathland areas as proposed in the original proposal. In this way we are able to focus more on the sub-surface hydrology of the undisturbed Old forest and an adjacent plantation with the aim of understanding the pedogenesis of forest soils, spring development and UK forestry in view of flood management reduction.

To investigate spring development in forest and sub-surface hydrology, the *in-situ* hydraulic conductivity was confined to two representative areas within a 40 year old plantation and an adjacent ~300 year old Forest. The proposed work to quantify local past disturbance of the Rothiemurchus Forest, was replaced by investigating soil moisture within the two sites and investigating the larger context of forest distribution and hydrology within the moraine terrain. The proposed changes restructured the project into the following sections.

1. Evaluation of Rothiemurchus area, which includes a survey of area and spring locations.
2. Creating a rational and choosing appropriate sites to investigate the proposed hypotheses.
3. Site evaluation of the chosen study areas: old Scots pine forest and mature Scots pine plantation
4. Investigating the wider area of the two chosen sites:
    - Aerial survey of tree distributions in the old forest to understand patterning of tree distribution.
    - Transect survey of peat depth survey to understand peat depth within moraine topography
5. Installation and analysis of automatic soil moisture sensors and rainfall within two representative sites within old forest and adjacent mature Scots pine plantation.
6. Measurement of *in-situ* hydraulic conductivity within adjacent Old forest and plantation forests.

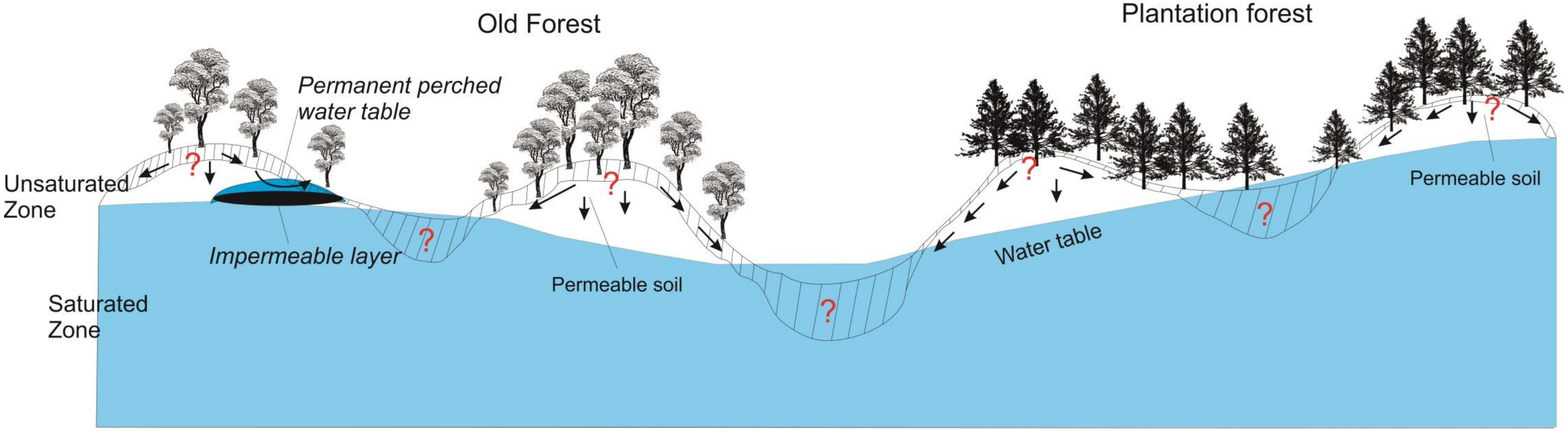


Figure 1) Revised conceptual model of sub-surface water flow (shown as arrows) in a moraine landscape. The hatched area is the subsurface organic layer and the question mark points are the main areas under investigation within the Old forest and the Plantation forest.

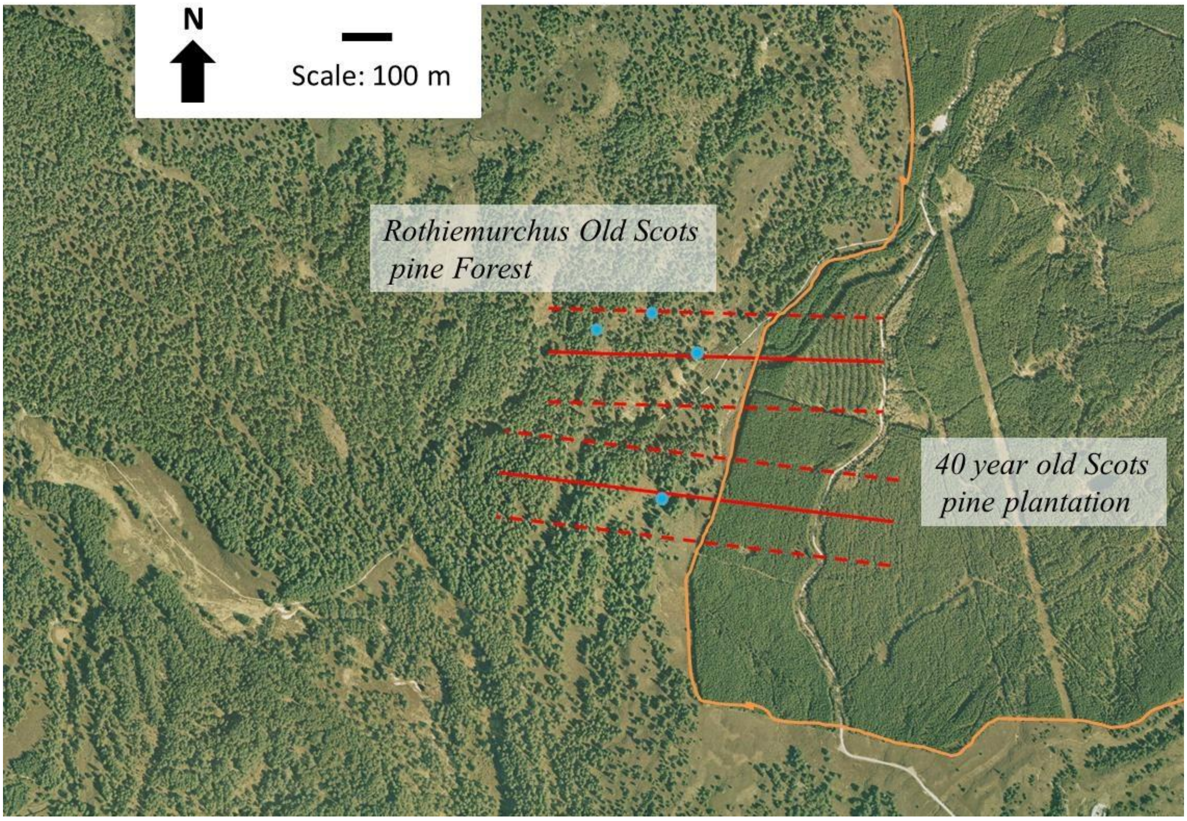
1.3 EVALUATION OF ROTHIEMURCHUS AREA

The Rothiemurchus Forest area was evaluated on foot and by mountain bike following accessible footpaths and bicycle tracks and also a number of off-path routes were chosen. The area was evaluated in terms of forest growth, soil types and geology.

The bedrock of the Rothiemurchus area consists of micaceous psammite (sandstone). Superficial geology is mainly morainic deposits, till, glaciofluvial fan and ice deposits, alluvium in main river channels and areas of peat in topographical depressions (shown in Figure 2). The area is typical of Bog woodland in the Cairngorms, as described by Special Areas of Conservation (SAC)[1]. During the site evaluation it was observed that mature scots pine trees were dominant on moraine crests and were absent in the topographical depressions between moraines. According to the Forestry Commission, the chosen Old Forest (*Pinus sylvestris*) area was planted or left to regenerate from 1750 and the adjacent *Pinus sylvestris* plantation was planted using imported seed in 1971. Taking into account the glaciated topography and the relationship of the mature forest transects were chosen for the spring survey (Figure 2) with the following criteria:

- They were representative of the Rothiemurchus area
- Each site located within the plantation forest area and undisturbed forest were adjacent to each other and on similar superficial geology
- The spring survey transects crossed both plantation forest and undisturbed forest.

[1] http://jncc.defra.gov.uk/ProtectedSites/SACselection/sac.asp?EUcode=UK0016412



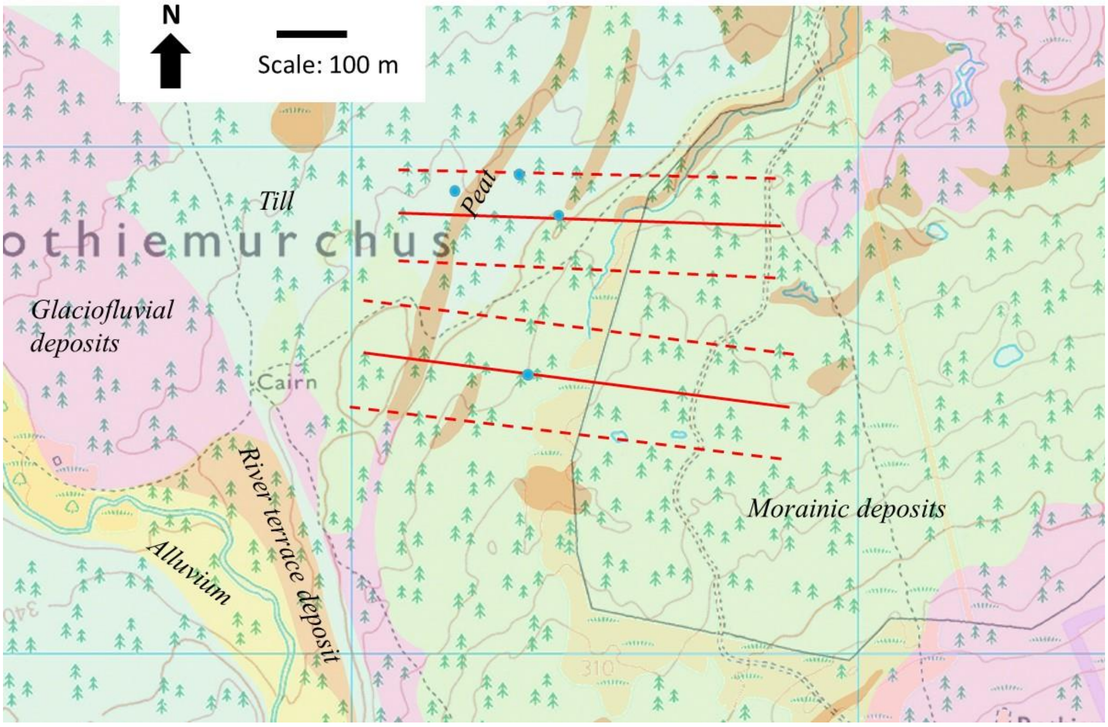


Figure 2) The top image shows an aerial view of the study area. The orange line delineates the boundary between the forest plantation area and the Old Rothiemurchus forest area. The bottom image shows the areas of superficial geology. The red lines indicate the two transect areas and the blue dots locate the positions of springs found during the survey. (Source: British Geological Survey, 2013. Aviemore Scotland Sheet 74E. Superficial Deposits, 1:50 000 Geology Series. (Keyworth, Nottingham: British Geological Survey).

1.3. THE SPRING SURVEY RESULTS AND DISCUSSION

During March 2015, four springs were found within the Rothiemurchus Forest and no springs were observed in the Scots pine plantation area; an example is shown in Figure 3a. The locations of the springs are given in table 1 and shown in Figure 2, as blue dots. The spring water conductivity, pH and temperature were measured and results are given in Table 1). All the springs were located near the break in slope of the moraine, which is a common position for spring occurrence due to perched water tables. Over the duration of the project these springs were observed to be permanent, even during October 2016 (the direst period during the project).

The only water found in the plantation area was stagnant open water (an example is shown in Figure 3b), situated in depressions between moraines and a flowing stream that originated from outside of the plantation. During the spring survey it was observed that there were undulating changes in elevation related to moraines within the forest plantation, which could not be seen on the aerial photographs or the digital elevation model.

Within the survey transects, dominant differences between the adjacent Old Forest and plantation areas were observed and are summarised in Table 2.

ID	Location	Conductivity (µS/cm)	pH	Temperature (°C)
Spring 1	NH 94414 07860	52.9	5.07	5.1
Spring 2	NH 94381 07937	75.2	6.07	4
Spring 3	NH 94208 07904	46.1	5.26	2.4
Spring 4	NH 94349 07556	44.3	4.93	3.8

Table 1) The locations of observed springs and measured water conductivity, pH and temperature during 03/03/2015.


a)


b)

Figure 3) a) The Old forest: Spring 1; an example of a spring, which is actively surfacing at the location shown to form the source of a small burn. b) Forty year old plantation: A pond in the forest plantation, which is not considered a spring, as there was no active flow of water in the area.

Rothiemurchus Old forest Scots pine	40 year old Plantation Scots pine
The present forest (*Pinus sylevestris*) was planted since 1750 and managed as a hunting forest for the last 500 years.	Planted as a plantation (*Pinus sylvestris*) for wood harvesting 40 years ago. The area was drained before being planted.
The forest is left to naturally regenerate. Trees are widely space (>10 m apart) and have varying ages. Trees are mainly mature and over 200 years old.	The plantation is planted in lines, with drainage lines between each row. The trees are between < 1 m to 3 m apart.
The organic layer above ground is very variable. At times organic mounds of sphagnum and dead wood can be at > 1m deep at the ground surface.	There is little organic material above ground within the plantation in comparison to the Old forest.
High biodiversity of understory: heather (*Calluna vulgaris*), blaeberry (*Vaccinium myrtillus*), bearberry (*Arctostaphylos uva-ursi*), Sphagnum species (*warnstorfii* and *auriculatum*)	Low biodiversity of understory: small patches of Heather (*Calluna vulgaris*), Blaeberry (*Vaccinium myrtillus*)
There were relatively few windblown trees in the Old forest area.	There were many windblown trees, particularly located in depressions between moraine crests where water ponds.
 Example of the Old forest understory	 Example of the understory of the plantation forest

Table 2) Summary of observed differences between the two areas: Old forest and Plantation forest.

Although the Old forest and Scots pine plantation were on the same superficial geology and bedrock, the differences between them are striking as illustrated in table 2.

Considering that there was a relatively large amount of snowfall during the winter of the spring survey, the ground of the Scots pine plantation was unexpectedly dry. The absence of springs in the Scots pine plantation could be because: 1) the thick canopy cover prevents rainfall from striking and infiltrating the soil surface, 2) the relatively shallow organic soil layer causes soils to have less permeability, reducing water infiltration and 3) forest transpiration rates, reduce soil moisture. To investigate the possible reasons for the absence of springs in the plantation we used the following rationale in section 1.4.

1.4. RATIONALE

3. To investigate hypothesis 1) *as these forests develop, the root system creates macropores and increases organic matter concentrations within the soil/root layer, optimising on the one hand to store water in the more organic soil and the other hand to allow water to flow via old root channels,* soil permeability will be investigated in terms of field saturated hydraulic conductivity (*Kfs*) to understand how rainfall becomes partitioned within the soil layer. The rational for this is shown in figure 4, where rainfall can be partitioned via several pathways. If rainfall intensity is higher than the maximum rate of soil infiltration, infiltration excess overland flow occurs (shown as 1 in figure 4). If rainfall is lower than maximum rate of soil infiltration, it will enter the soil system. Vertical water infiltration will continue to flow vertically if unimpeded to the groundwater aquifer flow (2 in Figure 4). If infiltrating rainfall reaches an impermeable layer (3 in Figure 4), water will flow within the sub-surface soil layer and travel laterally downslope. If the sub-surface profile becomes saturated, water will be forced under pressure to the surface, creating a spring (4, Figure 3).

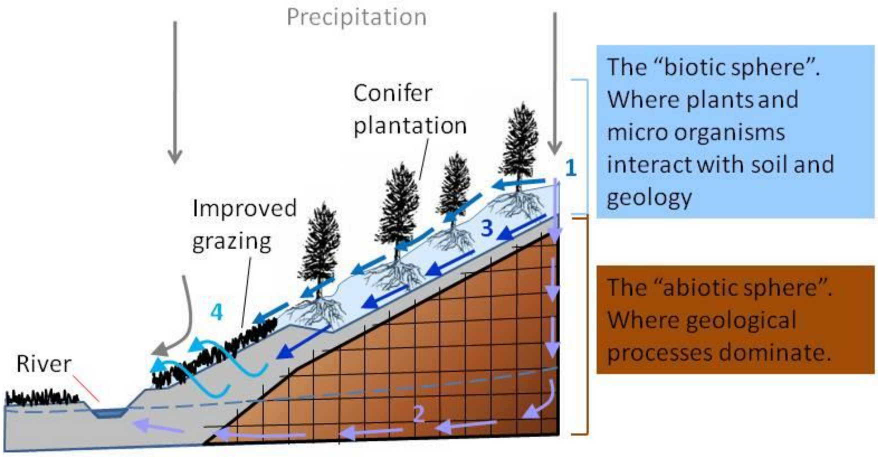


Figure 4 (1) Infiltration excess overland flow, (2) groundwater flow, (3) sub-surface stormflow –interflow, (4) saturation overland flow (Dunne and Leopold, 1978, Fig 9.1)

1. To investigate hypothesis 2) *springs develop within and around mature forests because their rooting systems interact with the soils in such a way as to form permanent and/or ephemeral perched water tables*, soil water contents, soil permeability, local topography and soil depth will be investigated. The rationale will be to understand how springs form within the moraine environment. A spring is the point where water flows out of the ground under pressure transmitted through the water, as it lies as a continuous body in the voids of sub-surface material (Bryan, 1919). Springs generally are formed by perched water tables, i.e. groundwater that is separated from the main groundwater body by an impermeable layer (as shown in the conceptual model, Figure 1). In the highlands of Scotland, as explained by Averis (2003), the areas where water upwells is often covered with cushions of mosses, where at the downslope edge of upwelling water a streamlet or rill may emerge.

Because of the environmental complexity of the moraine topography in Rothiemurchus, a System Thinking approach (described by (Kauffman, 1980) was used to understand how the different forest types interact with the surrounding environment. Springs may form through feedback loops that facilitate constant flow of water from the water table to emerge at the ground surface, or from a perched water table (Figure 5).

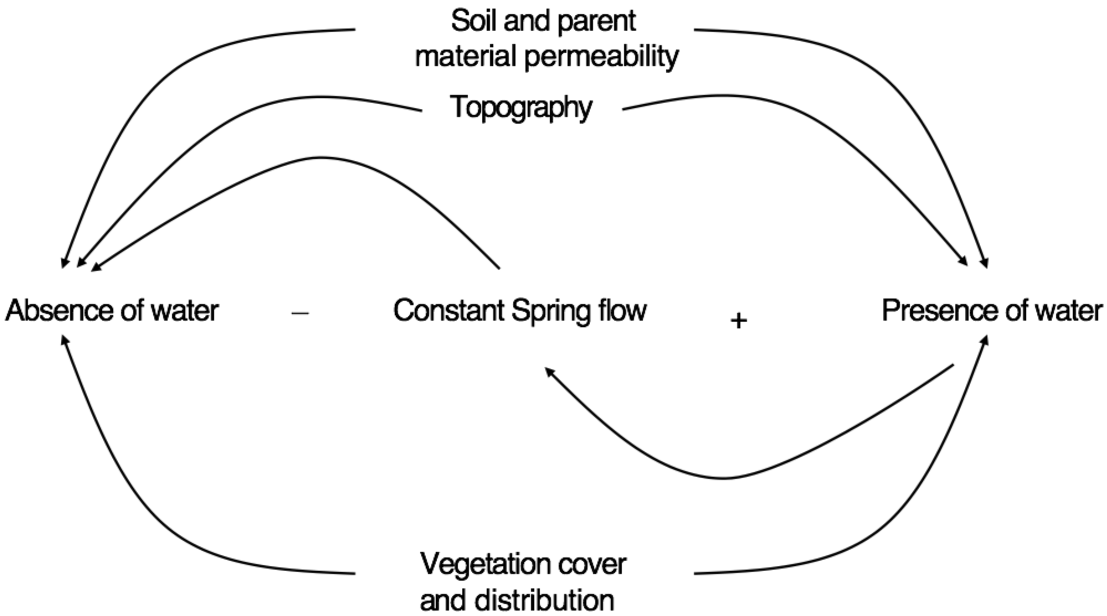


Figure 5) Positive and negative feedback loops for spring formation

2 Evaluation of Chosen field sites

To install soil moisture sensors and measure soil permeability within a mature plantation and Old Forest in the Rothiemurchus estate, two site areas, Old Forest and Plantation, were chosen (shown in Figure 7) for the following reasons:

- They are located on the same psammite micaceous bedrock and moraine system.
- The two forests are adjacent, although there is a mire between them.
- The sites are 380 m apart and there is 15 m difference in altitude between sites. These relatively small differences will ensure similar weather conditions throughout the year.
- Both sites are situated downslope below moraine crests, above the break of the slope and are easily accessible.

The plantation area had been drained before planting in 1971. Saplings were planted on the tops of ridges and furrows to allow free drainage. It is still possible to see the ridging and furrows within the plantation as explained later in (Section 3.3). The area is not fenced today and deer are able to roam through this forest area. It is expected that the plantation will be cut down within the next year.

In the Old Forest site, there is a seepage area at the lowest point, within a depression surrounded by trees, which was observed to stop flowing during dry intervals. Five metres below this point was a permanent spring. In the plantation site there were no continuous springs.

The Old Forest area is within the Rothiemurchus Estate Pinewood area, and the trees within the chosen study area are dated from 1750. The woodlands of Rothiemurchus have been managed for centuries for grazing, deer stalking, timber production and nature conservation. According to Piers Voysey, (the estate forester since 2010) during the 1800s tree felling and commercial planting were dominant landuses; later there was a pulse of forest regeneration and deer stalking, but by the 1980s overgrazing persisted due to high deer numbers (pers com., 2016). Today the forest is regenerating, due to the control of deer populations and the important conservation significance of the Rothiemurchus forest area that is recognised as a Site of Special Scientific Interest (SSSI) and is part of the Cairngorm National Park and Natura 2000 designations.

2.1 THE WIDER AREA BETWEEN THESE TWO SITES

To understand the topographical situation between the two sites (in answer to the conceptual model in Figure 1), the relationship of moraine positions in terms of tree and peat depth distributions within the Old Forest and the adjacent plantation, were studied by:

1) An aerial and field survey investigation to understand the relationship of moraine positions and tree distribution in the Old Forest and adjacent plantation.

2) A field survey of peat depth within the Old Forest and adjacent plantation.

To characterise the moraine system, a simple set of morphological types were chosen to best reflect the overall shape of the landscape. The area has a dominant topographical elevation, i.e. the moraines overlay a dominant valley slope, which increases from the valley bottom towards the mountain slopes. The topographical positions were categorized into four groups:

- Upslope: the moraine slope facing upslope towards the higher dominant elevation
- Downslope: the moraine slope facing downslope towards the lower dominant elevation
- Depression: considered to be <2 degree slope angle; delineated from the break in the moraine slope (downslope) to the break in the opposite slope (upslope).

- Crest: considered to be <2 degree slope angle; delineated by the change of the moraine slope at its higher elevation.

The locations of these four categories are shown in Figure 6.

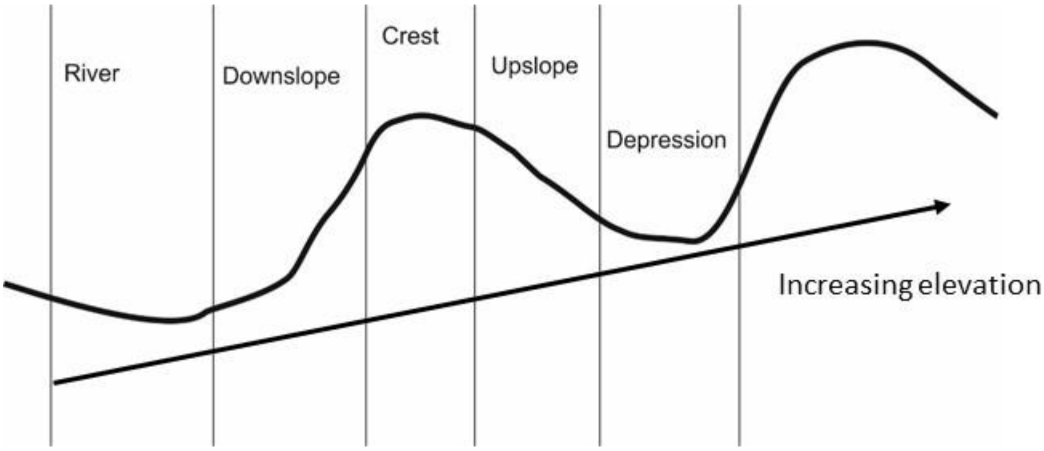


Figure 6) The position of each morphological type in relationship to moraine topography shape and elevation.

2.1.1 Topographic study and field survey of Scots pine distribution and moraine system in the plantation area

Studying aerial photographs with a DTM was not possible in the plantation because the canopy was so dense that the Digital Terrain Model (DTM) included tree heights, because the LiDAR signal could not penetrate through the canopy to the ground. Using a dGPS was problematic within the plantation, because the dense plantation canopy prevented accurate signals to estimate elevation. The accuracy of the dGPS heights was ±0.6 m for the few points that could be obtained under the plantation canopy.

To have an overall understanding of the moraine system within the plantation, stereo aerial photography and SOCET SET software were therefore used to determine differences of elevation within the plantation. This enabled the moraine system to be digitised, within the area surrounding the two sites (shown in Figure 7). It was difficult to digitize the smaller moraine mounds, as tree canopy sometimes became confused with the micro topography. However, Figure 7 shows the complexity of the terrain, where crests and depressions of the moraine system are defined, showing the landform patterns of the rising and falling micro topography and where streams develop in moraine depressions. Investigating the overall, area, also provides an understanding of dominant direction of water flow, for each chosen site (Shown as arrows in Figure 7).

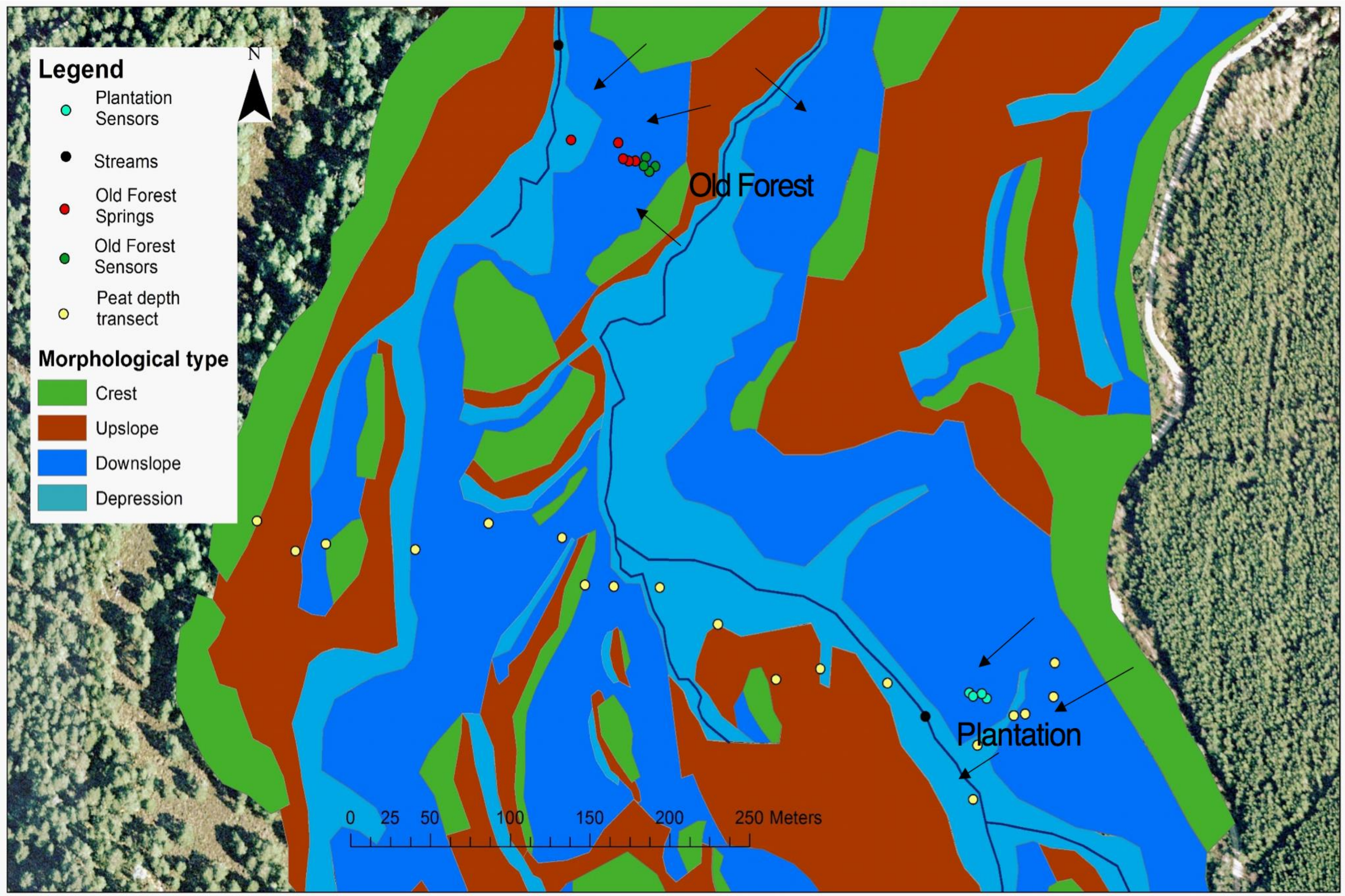


Figure 7) The rising and falling moraine micro topography of the two sites. Arrows show the direction of water movement for each site and black lines are permanent water.

A field survey within the plantation suggested that the majority of wind-blown trees (trees that have been blown over) occurred in wet moraine depressions (figure 8), creating open gaps within the plantation canopy.

Figure 8) Fallen trees in a 40 year old plantation within areas of depressions.

2.1.2 Aerial survey of tree distributions in the old forest to understand patterning of tree distribution.

2.1.2.1 METHODOLOGY TO CLASSIFY TERRAIN MORPHOLOGY

Aerial photography of the Rothiemurchus Pinewood area showed patterns of mature trees aligning along moraine crests and being absent in boggy areas. Therefore mapping of morphology was carried out using ArcGIS, using a combination of a 5 m resolution DTM and five transects were chosen based on clearly identifiable examples of the main morphological features being studied. The transects themselves were of varying lengths, most starting at the upslope end with the transition from bedrock to deposit-covered terrain, and ending with a significant change in morphological character, normally a large river channel. Each transect was buffered to 50m, giving a 100m-wide swathe of study area, and points were used to locate each tree top in the old forest on the aerial photos (Figure 9).

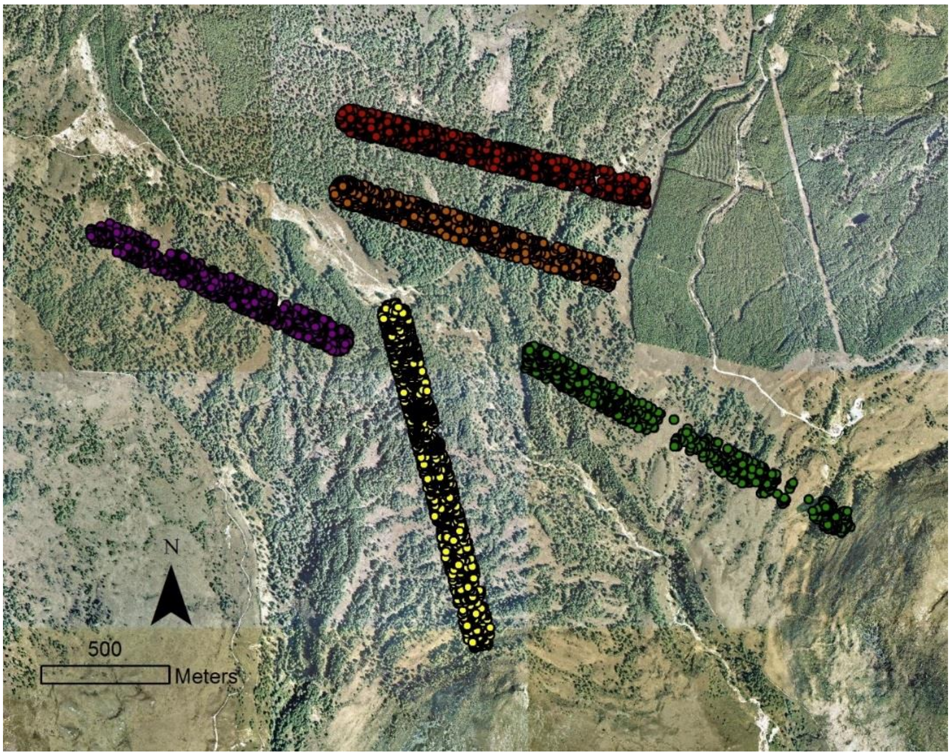


Figure 9) The five transects within the Old Forest study area. Each point is the top of a tree.

Using a combination of digital slope model (DSM) and aerial photographs, lines were mapped on each transect at distinct breaks in slope, both at moarine base and crest. In many cases this was straightforward as breaks were clearly visible on either or both the photography and DSM hillshade models (Figure 10). The topography was catergorised in the following way:

Upslope (Tn-UP): the moraine slope facing upslope towards the higher dominant elevation

Downslope (Tn-DO): the moraine slope facing downslope towards the lower dominant elevation

Depression (Tn-DE): considered to be almost <2 degree slope angle; delineated from the break in the moraine slope (downslope) to the break in the opposite slope (upslope).

Crest (Tn-CR): considered to be <2 degree slope angle; delineated by the change of the moraine slope at its highest elevation.

River (Tn-RI): The area which coincides to river banks and the river.

Figure 10) Close-up examples of transects to classify the moraine terrain. UP is Upslope, DO is Downslope, DE is Depression, CR is Crest and RI is river.

Within each transect the tops of trees were located using aerial photography. Each tree was located by adding a point in Arc GIS (shown in Figure 9) within each transect. The areas for the morphological types for each transect were estimated and the number of trees were counted to provide tree densities for each morphological type in units per m^2.

2.1.2.2 Results of Scots pine distribution and moraine location

The results of Old Forest tree densities in relation to morphological areas are shown in Figure 11. Using the Anderson-Darling test, tree densities from all five transects were not significantly different from a normal distribution and therefore Analysis of variance (ANOVA) was used to test for significant differences of tree densities between the different moraine positions. Overall there was no significant difference ($p = 0.075$) comparing all four positions (crest, depression, downslope and upslope), but the Fisher Method, which compared the tree density means of each of the moraine positions, showed that the mean tree densities were significantly less ($p < 0.05$) in the moraine depressions than on moraine crests and slopes.

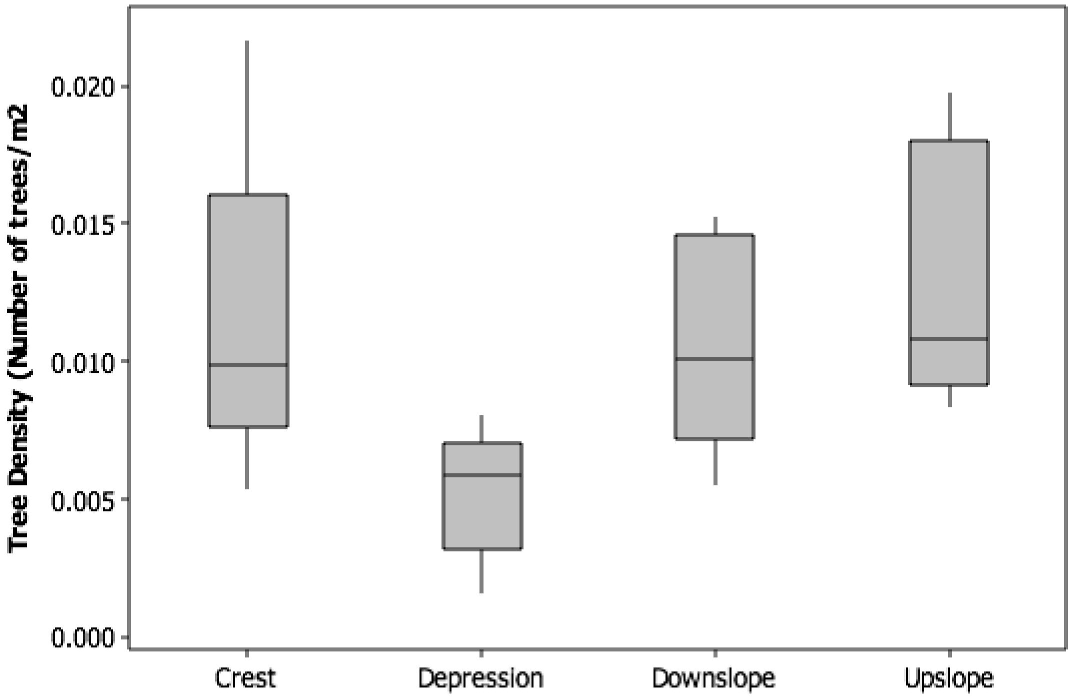


Figure 11) Results of tree densities within different moraine morphological units.

2.1.3 Measuring peat depths within Old forest and 40 year old plantation.

The peat depth survey (shown as yellow dots in Figure 7) was undertaken to understand the relationship of the moraine landscape and peat depth in the both the Old Forest and the forty year old plantation.

2.1.3.1 METHODOLOGY TO MEASURE PEAT DEPTH

A 400m transect was surveyed by taking measurements on the crest, slope and depressions of moraines within the 40 year old plantation and ~300 year Old forest. An avalanche probe was used to probe through the peat (as shown in Figure 12) and when it stopped at a hard surface the depth of the probe was noted. Five points were measured at each location.

Figure 12) Measuring peat depth in the 40 year old plantation

2.1.3.2 RESULTS OF PEAT DEPTHS MEASURED IN OLD FOREST AND 40 YEAR OLD PLANTATION

Peat depth was found to be highly significantly deeper (*p = 0.001*) in the Old forest area than the 40 year old plantation and highly significantly deeper (*p = 0.001*) in moraine depressions. These relationships are shown in Figure 13.

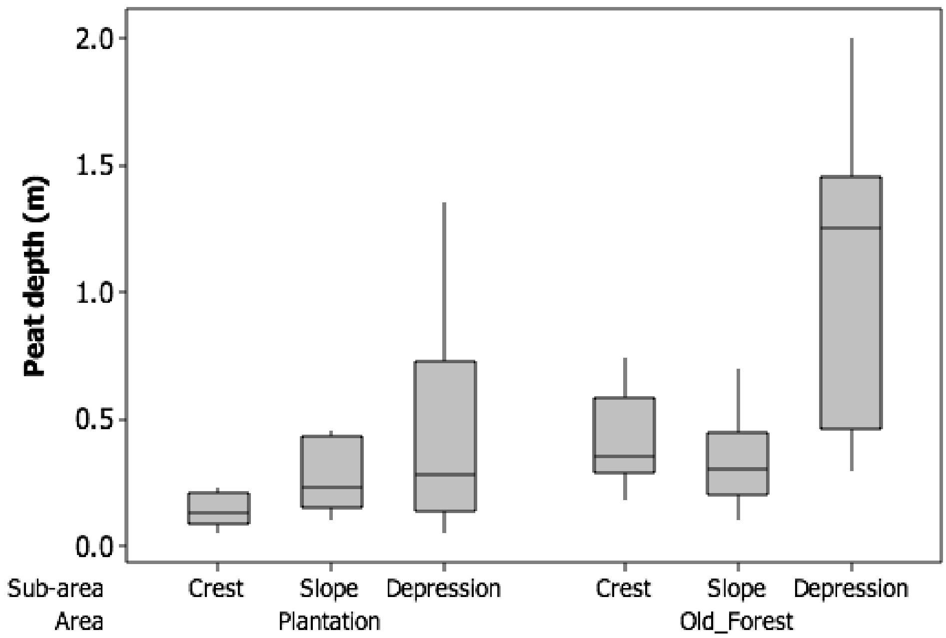


Figure 13) Results of the peat depth transect. Crest is the top of moraines, slope is on the slope of moraines and depression is the lowest point between moraines.

2.1.4 Discussion of wider extent of the Old Forest and adjacent plantation

Following the wider survey of tree and moraine distribution, the conceptual model in Figure 1 was redrawn to take into account the better understanding of geology, peat depth and forest location.

The re-conceptualised model shows the significantly deeper depths of peat in the moraine depressions, with thinner layers of peat on moraine crests, with peat being deeper in depressions under the older forest (Figure 13). The Older trees in the Rothiemuchus estate are positioned mainly on moraine crests and slopes (Figure 11) and the trees in the plantation are positioned regardless of moraine topography, although there tends to be a greater number of fallen trees in the moraine depressions (Figure 7).

Following the superficial geology stratigraphy shown in the Aviemore Superficial geology map (Sheet 74E[2]), the Ardveriki Till Formation is below the Morainic Deposit. The morainic deposits consist of poorly sorted gravel, sand and sandy diamicton forming boulder-strewn mounds. The Ardveriki Till formation is mainly diamicton, silty clayey, sandy and gravelly till, mainly a pale yellowish brown with clasts of micaceous-psammite with some granodiorite, porphyry and granite. The presence of till will create perched water tables, as the permeable morainic deposits overlie the less permeable till. Some of the moraine depressions are also likely to have fine sediments under the peat, which developed after glacial retreat, when ponding and slowing of water formed in the moraine depressions, depositing fine clays and silts. Such processes are explained by Benn and Evans, 1998, p.489[3]. Peat later developed on top of these more impermeable lake deposits.

[2] British Geological Survey, 2013. Aviemore Scotland Sheet 74E. Superficial Deposits, , 1:50 000 Geology Series. (Keyworth, Nottingham: British Geological Survey).
[3] Benn D. I. and Evans, D. J.A., 1998. Glaciers and Glaciation. Arnold, London.

The extent of impermeable layers are unknown, but they exist in many of the moraine layers in the Cairngorms and can be seen in some of the undercut moraines near to this site. These are included in Figure 7, showing the location of harder impermeable layers, creating multiple perched water tables. Because of the complexity of the Glacial fluvial geology in the Cairngorms, more investigation is needed to quantify how these perched water tables exist and are distributed across the Cairngorms.

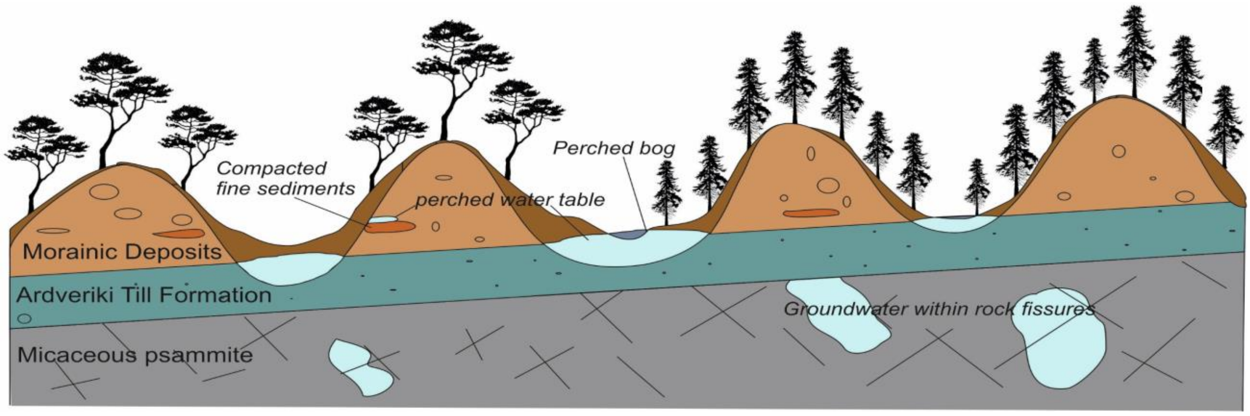


Figure 14) Re-conceptualized model of moraine topography, tree position, soil, water and geology. The Old Forest area is shown on the left and the Plantation is shown on the right side of the diagram.

3 Investigation of Old Forest and 40 year Plantation sites

3.1 INSTALLATION OF SOIL MOISTURE AND RAINFALL MEASUREMENT IN REPRESENTATIVE OLD FOREST AND PLANTATION SITES

The British Geological Survey had Delta-T Devices (Cambridge, UK) soil moisture sensors and a rain gauge, which enabled the possibility to instrument the two chosen areas, at the end of March 2015. Sensor positions for each site are shown in Figures 7 and 30.

Old forest site and rain gauge

Plantation forest site and rain gauge

Soil moisture sensor installed below a tree in the Old forest site

Soil moisture sensor installed below a tree in the plantation forest area

Figure 15) The Old forest and the plantation forest sites. Bottom photos are examples of how the soil sensors were installed.

An extra rain guage was bought from the funds available from this project, so that each site could be instrumented with a raingauge and four soil moisture sensors installed between 0.25 and 0.35 m soil depth at each site. The position of soil moisture sensors in the soil profiles and layout of instrumentation are shown in Figures 16 and 17 respectively. Sensors were placed near the soil/ sand

and gravel interface, unless peat depths exceeded 0.4 m, as shown for sensors 1 and 8 (Figure 16). Figure 17 shows the layout of the sensors within the two sites, where two sensors were installed in depressions (grey areas in figure 17) and two sensors were located in ridges (white areas shown in figure 17) and were installed in the direction of the slope. The sensors measured every 15 min. from 27th March 2015 to 8th September 2016. Unfortunately, in the plantation site, due to faulty batteries, the soil sensors in the plantation stopped logging during the winter from 30th October to 28th March 2016. A very dry period during October 2016, was also not measured, as the soil sensors were un-installed at the beginning of September 2016.

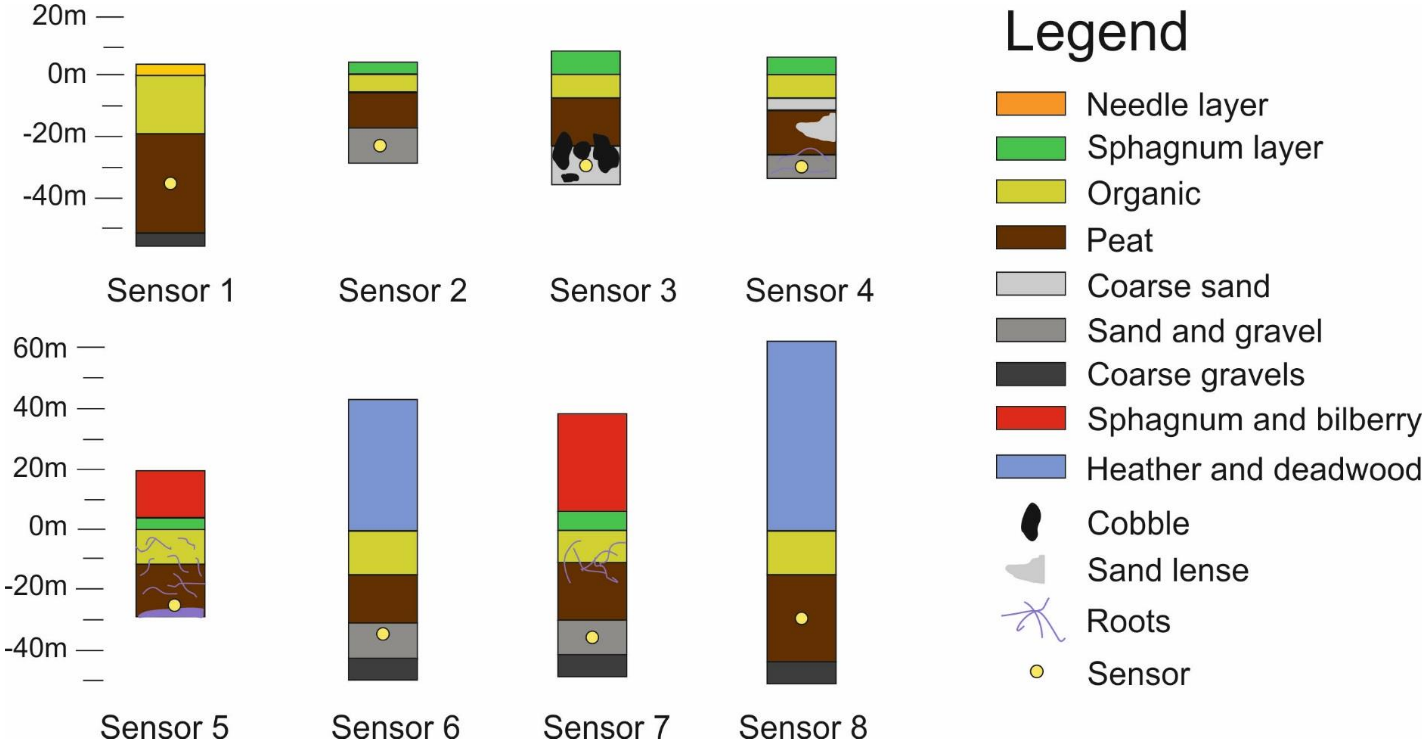


Figure 16) Graphical representation of the positioning of all soil moisture sensors. Sensors 1 to 4 are in the plantation and sensors 5 to 8 are in the Old Forest site. 0 m is ground level, below ground is negative figures and above ground (vegetation height) is shown as positive figures. Photos of each Sensor location are given in Appendix 1.

The layout of soil sensors were located in this way to provide some understanding of soil water infiltration and redistribution within the soil profile, to address the following questions

1) How much rainfall enters the forest canopy of both areas?
2) Is there sub-surface flow occurring downslope?
3) Do the depressions have greater soil wetness throughout the year in comparison to ridges?

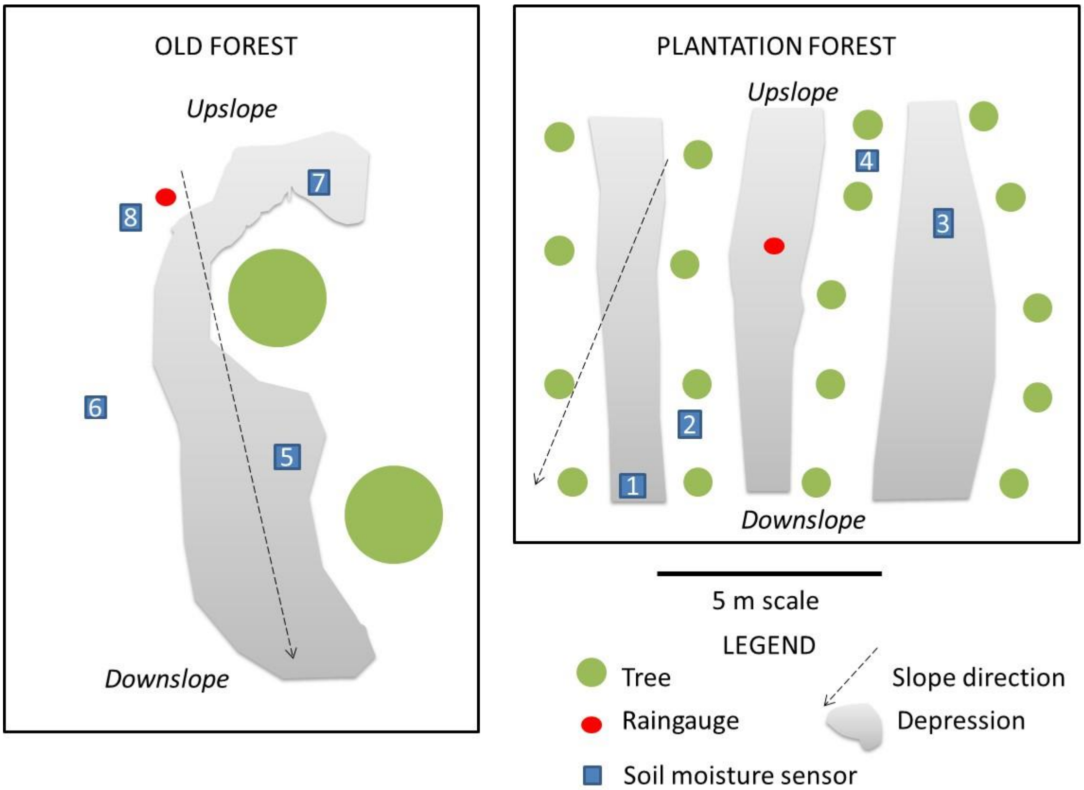


Figure 17) Field site instrumentation of the Old forest and the Plantation forest. Numbers relate to soil moisture sensor locations.

3.1.1.1 RESULTS OF SOIL MOISTURE SENSORS

Soil water contents measured at eight points from 27th March 2015 to 8th September 2016 are shown in Figures 18 and 19. It is unfortunate that soil moisture was not recorded for most of the winter in the plantation site. However, overall, the soil sensors in the plantation are all very responsive to rainfall, particularly for sensors 2 to 4 positioned in sand and gravel layers (Figure 16), these sensors tend to respond to peak rainfall within 20 hours. Here the soil profiles wet-up quickly in response to high intensity or long duration rainfall and then drain quickly, creating dynamic fluctuating soil water curves. Sensor 1 is located in peat and sensor 4 is located in a mixed sandy peat, and they have consistently larger soil water content throughout the year. Sensor 1 is not as responsive to rainfall as the other sensors. In the Old Forest, each sensor has a different dynamic in relationship to rainfall events. Only Sensor 6, located in sand and gravel, is very responsive to rainfall. This sensor quickly wets-up even during relatively low magnitude rainfall events and rapidly drains during drier intervals, creating a similar fluctuating curve to the curves in the plantation for Sensors 2 to 4.

In the Old Forest, Sensors 5, 7 and 8 do not respond to high intensity rainfall like the other sensors. All three sensors are below heather, bilberry and sphagnum mounds, but are all placed in different substrate. Sensor 5 is placed in organic soil above a mature tree root (Figure 16), which belongs to a 250 year old Scots pine and has the largest variation of soil water content in comparison to all other sensors (Figure 24). Considering the change in volumetric soil water content from 0.4 to 1 $m^3\ m^{-3}$ means that the soil sensor becomes fully saturated, suggesting that there is preferential flow, which is typical of the occurrence of root channels. The gradual reduction of soil water content during the summer even when there is rainfall also suggests active evapotranspiration taking place. Sensor 7 has a similar pattern to sensor 5, although the range of volumetric soil water content change remains narrower (from 0.38 to 0.62). Finally, Sensor 8 remains almost consistently at saturation throughout the year and this is the only sensor in peat below a sphagnum and bilberry mound.

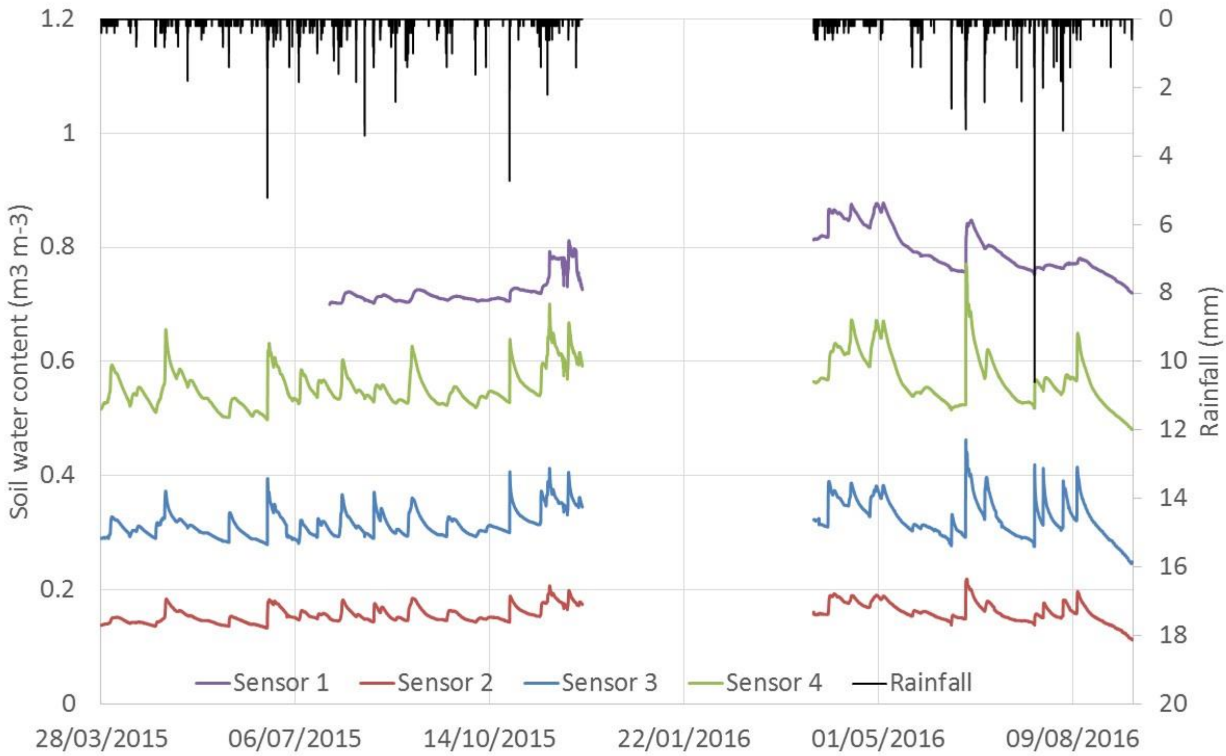


Figure 18) Soil moisture curves measured every 15 minutes in the plantation site

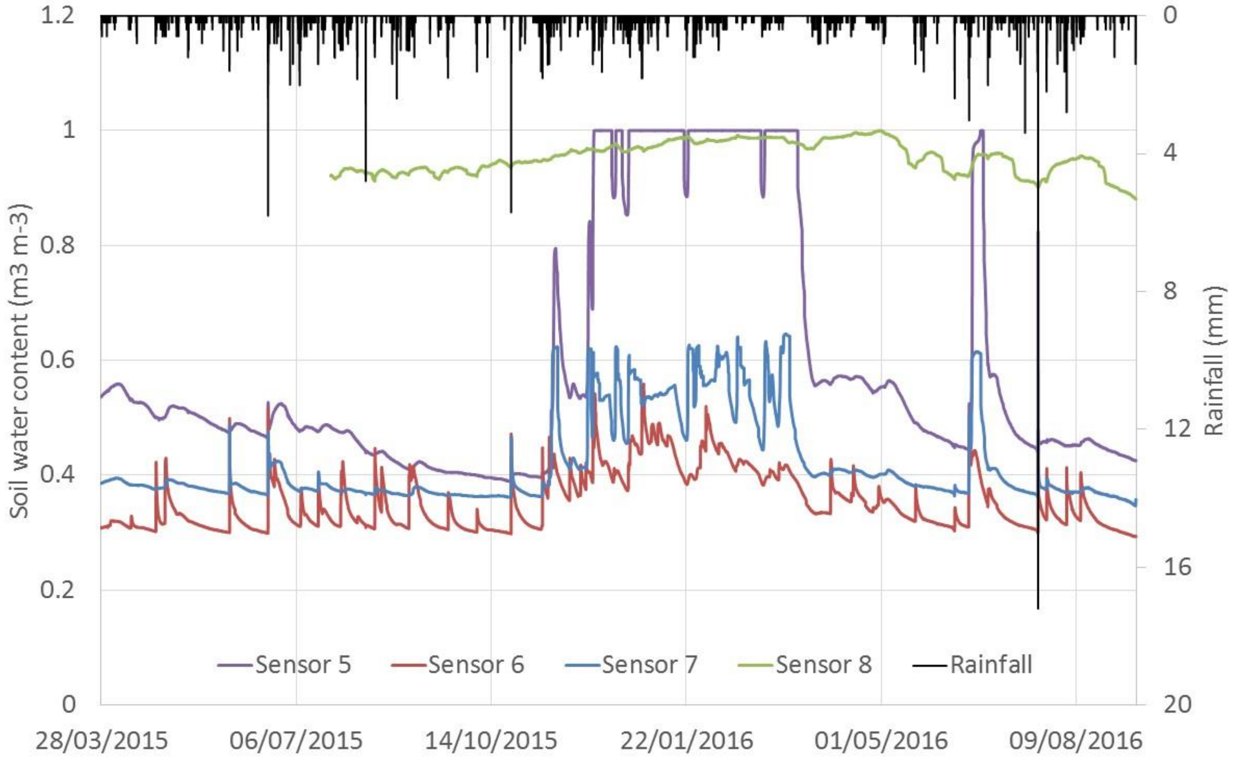


Figure 19) Soil moisture curves measured every 15 minutes in the Old Forest site

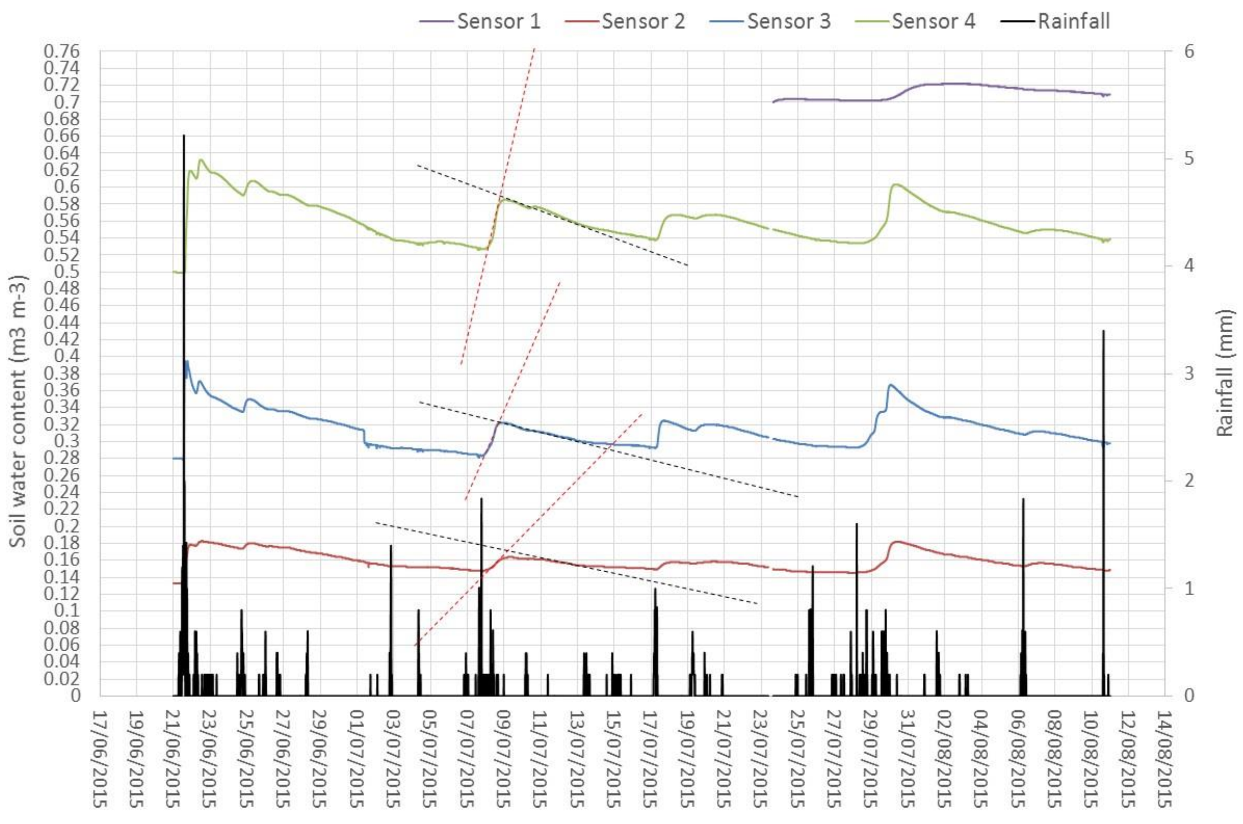


Figure 20) Closer inspection of soil water content changes between 17/06/2015 to 14/08/2015 in the plantation site. The dashed red lines show the gradient of water infiltration into the soil profile, from the onset of the water reaching the sensor to peak soil water content. The black dashed lines show the gradient of drainage and water loss from the point of peak soil water to a decrease in soil water content.

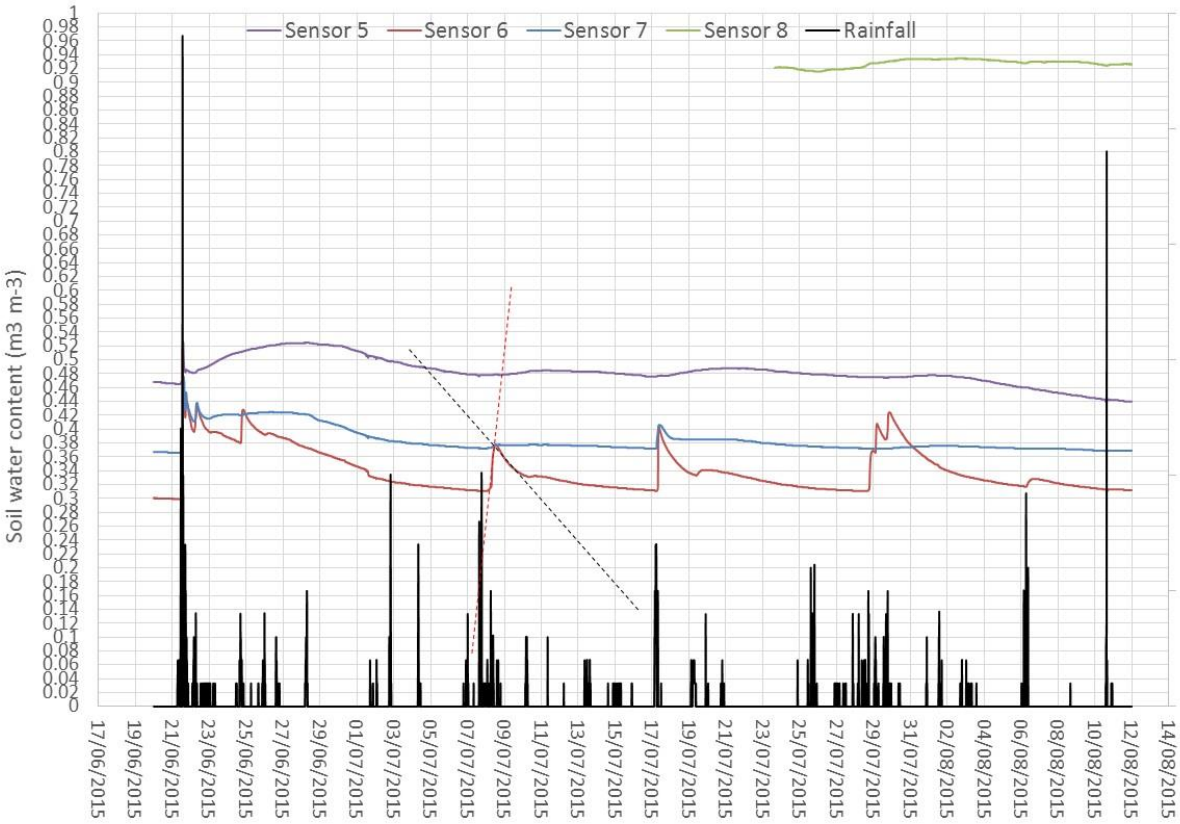


Figure 21) Closer inspection of soil water content changes between 17/06/2015 to 14/08/2015 in the Old Forest site. The dashed red lines show the gradient of water infiltration into the water profile, from the onset of the water reaching the sensor to peak soil water content. The black dashed lines show the gradient of drainage and water loss from the point of peak soil water to a decrease in soil water content.

Looking more closely at the wetting peaks of sensors 2, 3 and 4 in the plantation, the peaks occur approximately at the same time with the onset of rainfall; i.e. when rainfall is >1mm, or there is a series of low (0.8 mm), but consistent rainfall. Once the soil begins to wet-up there is a rapid rate of water infiltration to peak water contents, ranging from infiltration rates of 2 mm/day (Sensor 2) to 10 mm/day (Sensor 4). Drainage and water loss are slower from 0.4 (Sensor 2) to 0.8 mm/day (Sensor 4). In the Old Forest site, the rate of water gain and loss in the soil profile at Sensor 6 however is higher (e.g. water infiltration 18 mm/day and drainage and evaporation/ET 3mm/day). Figure 26 shows that Sensors 5 and 7 are relatively unresponsive to rainfall.

3.1.2 Rainfall between the two sites

Because the rain gauges were not heated during the winter, snow built-up in the rain gauge funnels. As the snow melted, the melt gave an impression of rainfall. This however was useful to understand infiltration rates of water, irrespective of whether the source of the water was rainfall or snowfall.

3.1.2.1 Results of rain gauge measurements between the plantation and Old Forest sites

Unfortunately, there was a technical fault with the Plantation datalogger, causing a loss of three months data during the winter. Therefore to be able to compare the rainfall quantity on both sites, the missing data of the plantation site was also removed from the Old Forest site and then cumulated. The resulting cumulated rainfall for the two sites is shown in Figure 23, showing cumulatively that the Old Forest received 134 mm more rainfall at ground level during the measurement period than the Plantation site.

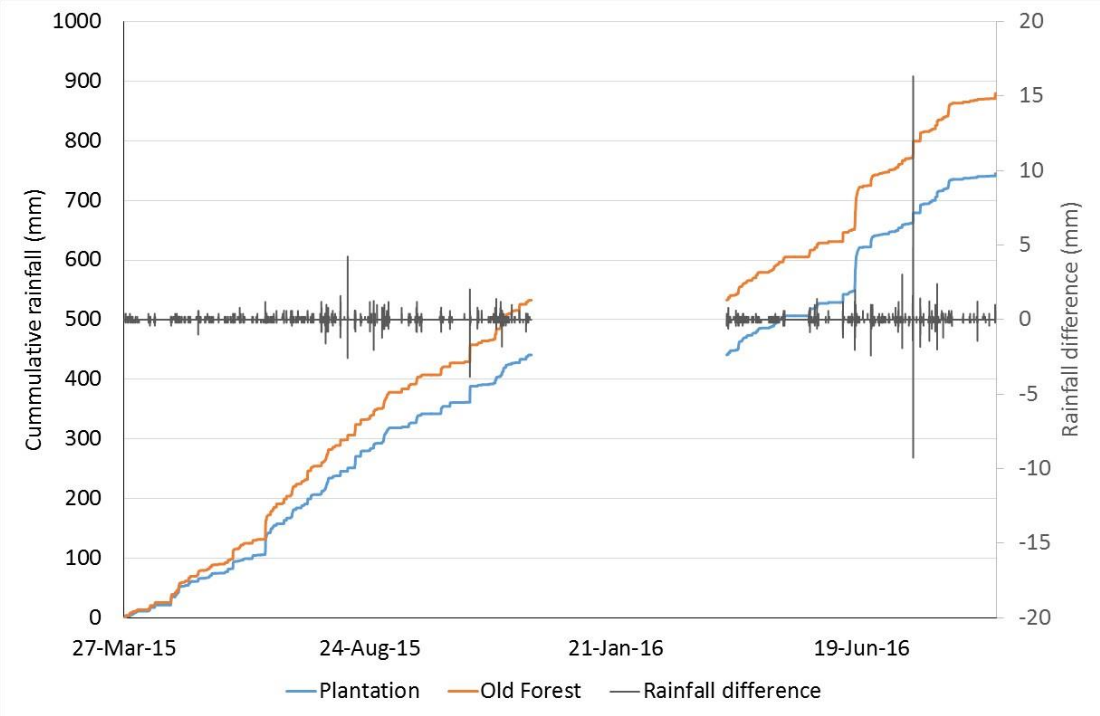


Figure 22) Cumulative rainfall and rainfall differences between plantation and Old Forest sites

Maximum 15 min. rainfall intensity was 5.2 mm in the Plantation site and during the interval when the Plantation rain gauge was not working, the Old Forest recorded 17.2 mm during the winter.

3.2 MEASUREMENT OF SOIL DEPTH AND VEGETATION HEIGHT IN OLD FOREST AND PLANTATION SITES

A 20 m x 15 m grid was delineated within each site area and divided on the ground into smaller 2.5 m grids. At each intersecting 2.5 m point, an avalanche pole was used to measure soil depth and vegetation height. Soil depth was considered to be from the level of the ground to the point where the avalanche pole strikes a gravel layer. Understorey vegetation height was measured to be from the ground to the top of vegetation branches.

3.2.1 Results of soil depth and understorey vegetation height between old forest and plantation sites

The Anderson-Darling test for a normal frequency distribution showed that the data for soil and vegetation depth were not normally distributed. This was partly due to outliers within the data (as shown in Figure 22). The non-parametric Wilcoxon-Mann-Whitney was therefore used to compare differences between soil and vegetation between the Old Forest and plantation sites. This test showed that soil depth and vegetation height were significantly greater in the Old Forest site than the plantation ($p = 0.0001$ for soil depth and $p < 0.0001$ for vegetation height). A box-plot showing the spread of data are shown in Figure 23.

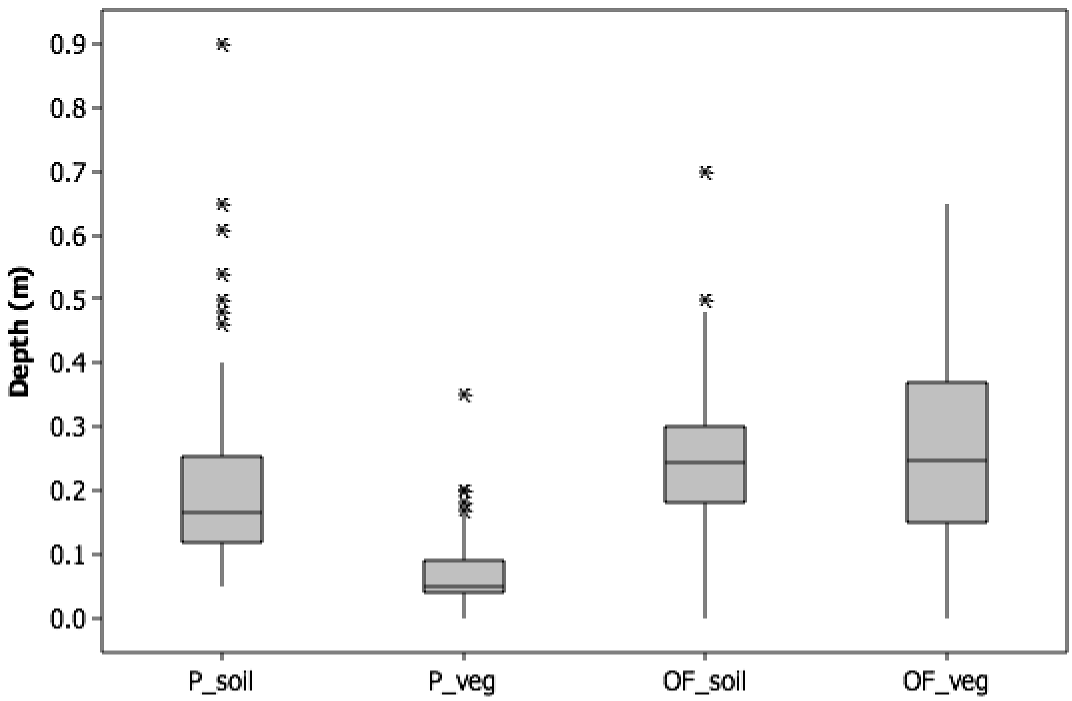


Figure 23) Results of soil depth and vegetation height. Psoil and OFsoil indicate the depth of soil for the plantation site (Psoil) and the Old Forest site (OFsoil). Pveg and OFveg indicate vegetation height for the plantation site (Pveg) and the Old Forest site (OFveg).

3.3 MEASUREMENT OF *FIELD* SATURATED HYDRAULIC CONDUCTIVITY WITHIN ADJACENT OLD FOREST AND PLANTATION FORESTS.

A Guelph constant head well permeameter (Reynolds, et al., 1983) was used to measure the field saturated hydraulic conductivity (*Kfs*) and hydrostatic pressure potential (φm) within the Old forest and the plantation forest sites (figure 24). Auger holes were generally augered to the gravel layer, which ranged between soil depths of 13 to 39 cm. *Kfs* was measured at the soil/gravel interface using the Guelph permeameter procedure. For each augered hole two infiltration rates (cm/min) were measured, one at a constant head of 5 cm and the other at 10 cm. Since the double-head permeameter method estimated negative *Kfs* and φm values for some of the augered holes, the single head method was preferred. Therefore the *Kfs* and φm estimated for the constant heads of 5 and 10 cm were averaged to provide average *Kfs* and φm values for each auger hole. Overall, a total of sixty auger holes were measured in the plantation and Old Forest sites from May to October 2016.

In the plantation, the holes were augered in either drainage lines/ depressions or within tree planted ‘mounds’, following the pattern trees in which they had been planted. As shown in Figure 25, the drainage lines and planted trees changed direction depending on slope angle. Because of the glacial debris in the Cairngorms, boulders exist within the moraine systems, but in the plantation site, these boulders seemed to have been redistributed to the ground surface and repositioned along edges of drains, when the land had been drained for tree-planting. Presently, these boulders are thinly covered by sphagnum and sometimes blaeberry.

	
Old Forest site	Plantation site

Figure 24) Using the Guelph permeameter to estimate field saturated hydraulic conductivity.

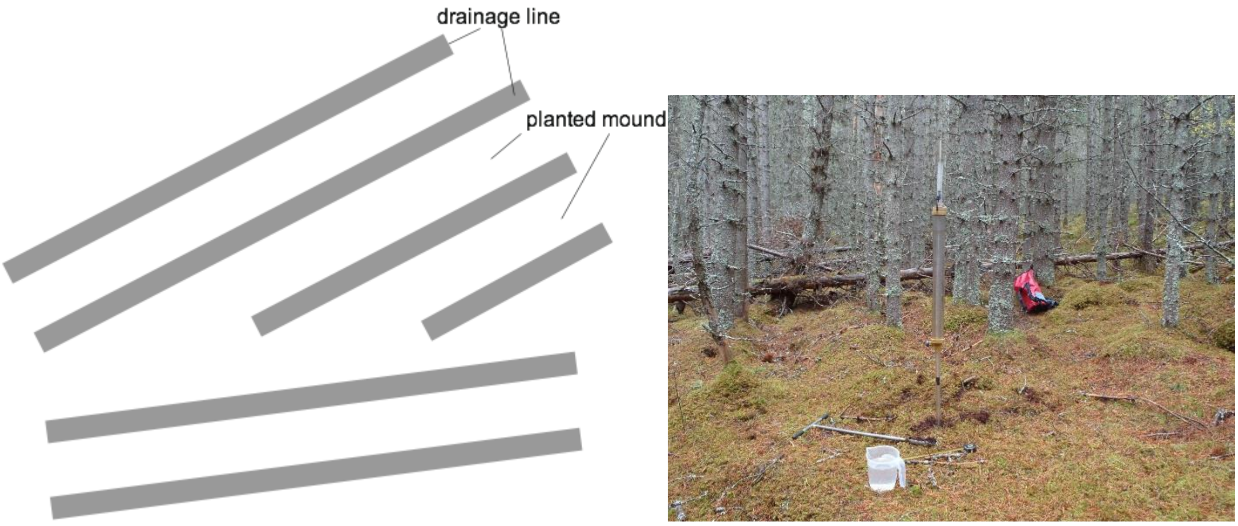


Figure 25) Guelph permeameter measurements taken within drainage lines (depressions) and planted lines (mounds) in the plantation site.

In the Old Forest trees were distributed depending on natural regeneration. There was a complex system of vegetation mounds under the expansive tree canopy where heather and sphagnum dominated or bearberry and blaeberry dominated with sphagnum. In some cases these vegetation mounds covered boulders that were part of the moraine system. Guelph permeameter measurements in the Old Forest therefore were taken within the natural pattern of depressions and vegetation mounds, as shown in Figure 26.

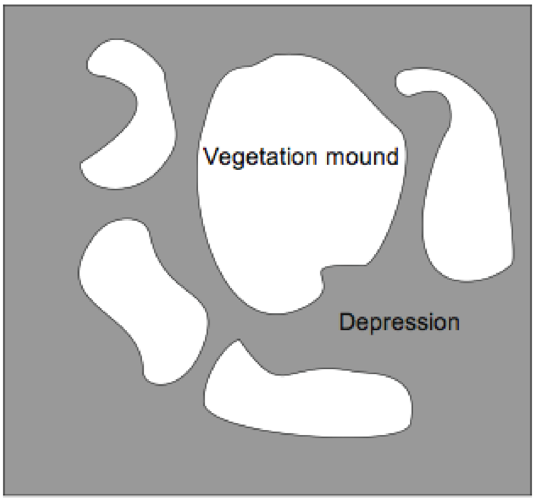


Figure 26) An example of the distribution of vegetation mounds and depression areas, which are the spaces between the mounds in the Old Forest site.

3.3.1 Results for field saturated hydraulic conductivity (*Kfs*)

Hydraulic conductivity is a highly variable soil property, where even samples taken within centimetres of each other can vary 10-fold or more (Soil Survey Division Staff, (1993). Because *Kfs* and *φm* are log normally distributed properties, the average *Kfs* and *φm* values (described in Table 3) were transformed using a log normal function and are displayed in Figures 27 and 28.

	Plantation		Old Forest	
	Kfs (cm/min)	Φm (cm^2/min)	*Kfs* (cm/min)	Φm (cm^2/min)
Number of values	30	30	31	31
Mean	0.399	0.0318	0.723	0.0405
Mean standard error	0.104	0.0076	0.240	0.0134
Standard deviation	0.567	0.0417	1.338	0.0746
Minimum	0.002135	0.0011	4.08251E-05	1.8905E-06
Lower quartile	0.058	0.0036	0.017	0.0009
Median	0.135	0.0110	0.057	0.0041
Upper quartile	0.683	0.0392	0.764	0.3540
Maximum	2.390	0.1709	4.801	0.2752

Table 3) Descriptive statistics for saturated field hydraulic conductivity (*Kfs*) and matric potential (Φm)

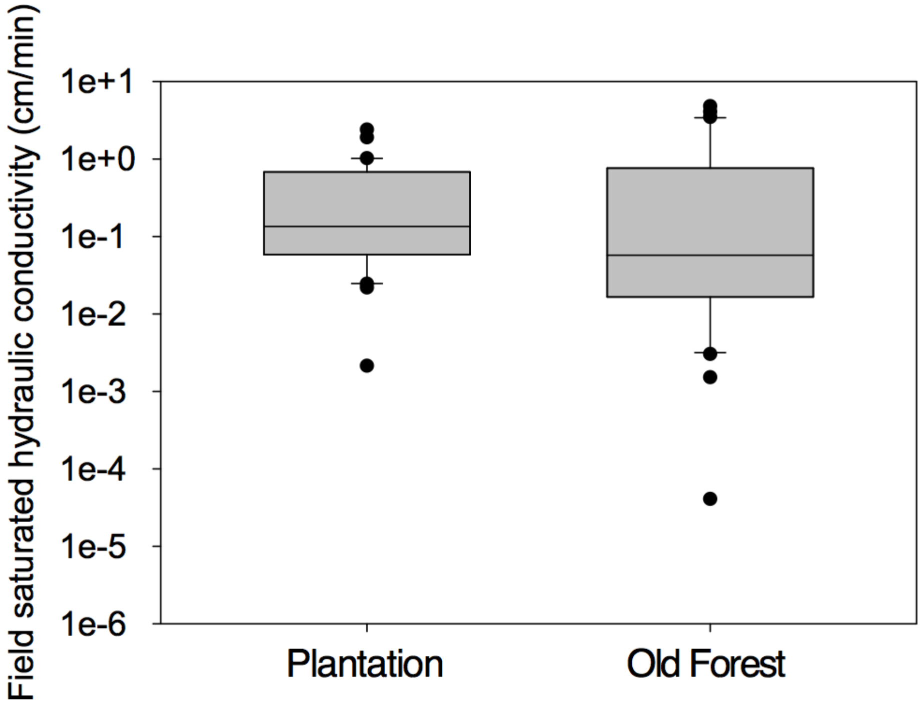


Figure 27) Field saturated hydraulic conductivity (cm/min) for the Plantation and Old Forest sites.

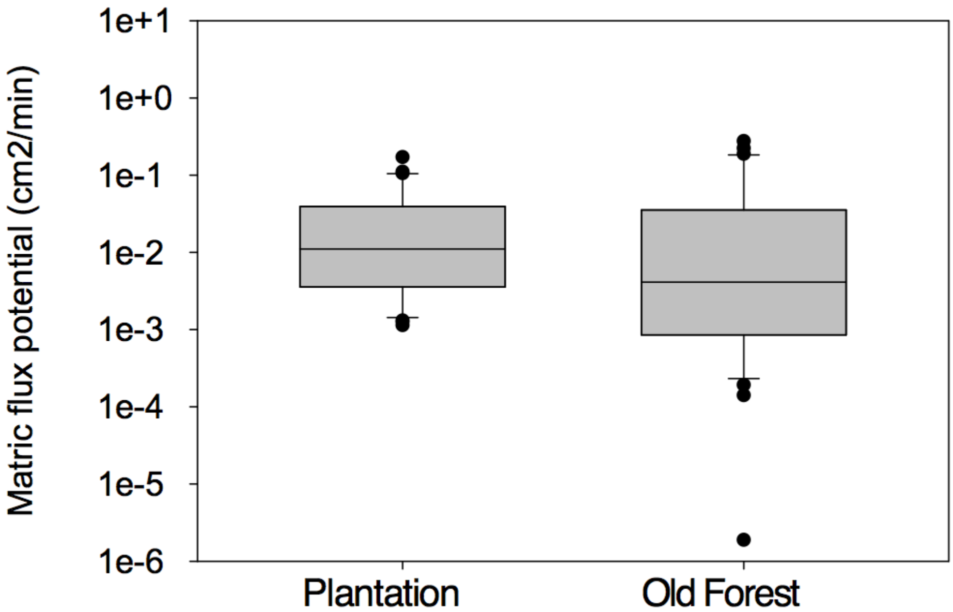


Figure 28) Matric flux potential (cm^2/min) for the Plantation and Old Forest sites.

The t-test and ANOVA assume that the data is normally distributed and the variances of the two samples are homogenous. Although the logged data are normally distributed, the variances of *Kfs* and *φm* between the Plantation and Old Forest sites are significantly different (Levene's test, p = 0.041 and p=0.013 respectively). Therefore, the Mann-Whitney U test was used to establish whether there were significant differences in saturated hydraulic conductivity between the Plantation and Old Forest sites. It was found that *Kfs* medians were not significantly higher ($p<0.05$) in the Plantation site than the Old Forest site (calculated at $p = 0.1821$), but was significantly different for *φm* (calculated $p = 0.05$).

Differences between log-transformed *Kfs* values measured in depressions and mounds for each site were found to be significantly larger in the vegetation mounds than the depression areas in the Old Forest site (p= 0.005), but were not significantly different in the plantation site (*p=0.35*). The raw *Kfs* values are shown in Figure 29.

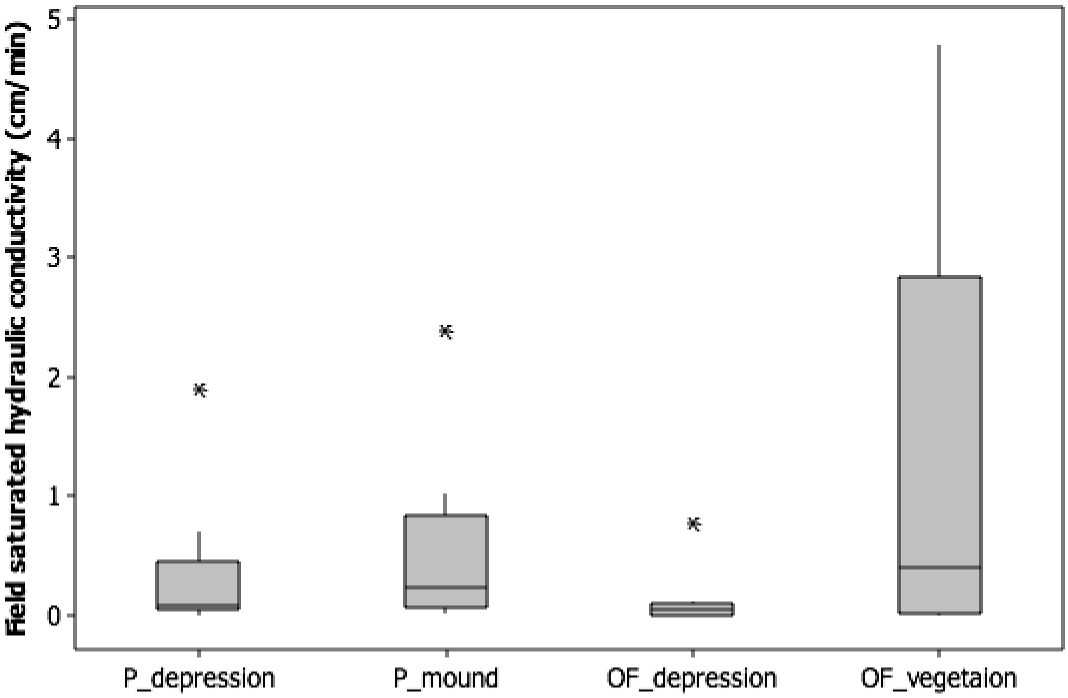
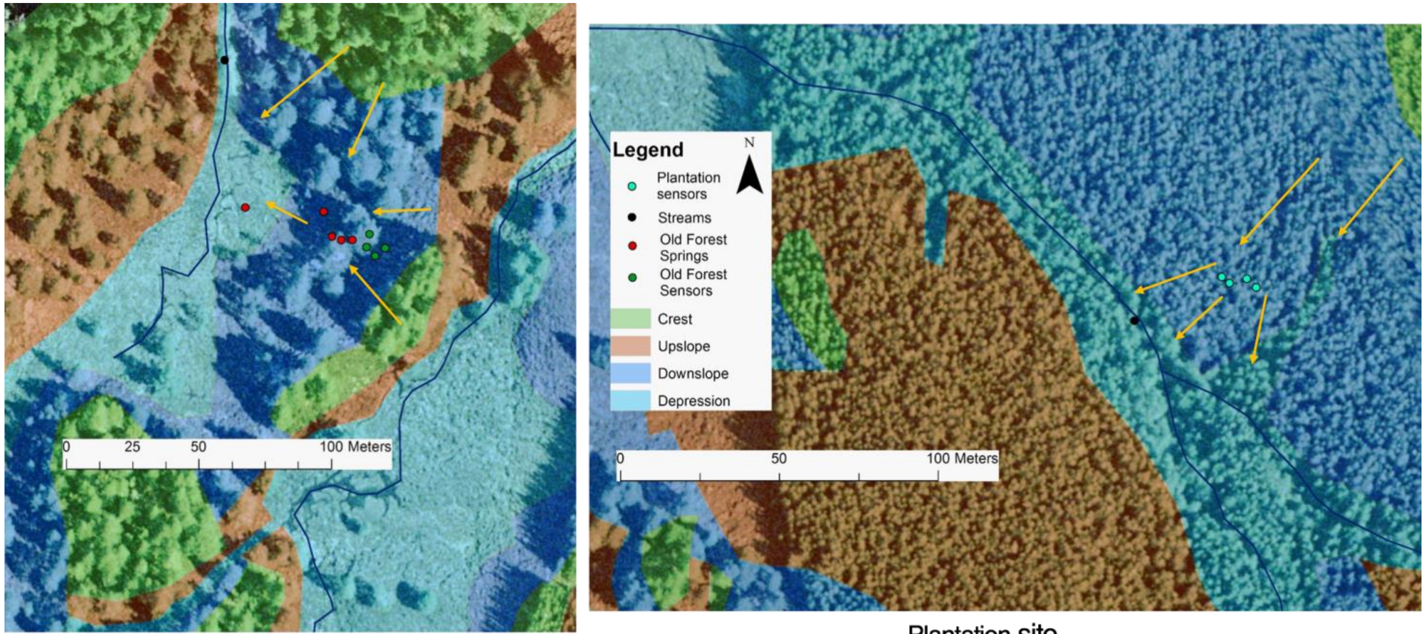


Figure 29) Field Saturated hydraulic conductivity in mounds and depressions within the plantation site (P_depression and P_mound) and the Old Forest site (Of_Depression and OF_vegetation).

It must be noted that during October 2016, soils were particularly dry in the plantation, because there had been no rainfall for three weeks. At the bottom of the slope in the plantation the deeper peat soil had become dry and friable and Geulph permeameter measurements in this area, flowed out of the permeameter without resistance. To check for peat cracking, four auger holes were augered to 10 cm width to allow for inspection with a torch and allow for a hand to enter the hole and check if there were cracks. It was observed that all four auger holes had cracks to more than 1 cm to 0.4 m soil depth. The Guelph permeameter therefore could not be used in these dry peat soils, as the cracks in the peat caused preferential water flow, bypassing macropores and causing error to estimate *Kfs*. In the Old Forest site however, even though it had not rained in this area, the peat had not dried out, and no cracking was observed.

3.4 SLOPE DIRECTION AND WATER MOVEMENT

The dominant direction of water flow within each site is shown as yellow arrows in Figure 30. Main direction of flow is downslope towards the stream depressions, this is particularly relevant for the Plantation site. In the Old Forest site, some water flows into the site from the northern adjacent moraine.



Old Forest site Plantation site

Figure 30) Direction of water flow (yellow arrows) and position of soil water content sensors and surface water indicated by blue lines within the moraine topography of the two sites.

4 Discussion

4.1 INVESTIGATING HYPOTHESIS 1) AS FORESTS DEVELOP, THE ROOT SYSTEM CREATES MACROPORES AND INCREASES ORGANIC MATTER CONCENTRATIONS WITHIN THE SOIL/ROOT LAYER, OPTIMISING ON THE ONE HAND TO STORE WATER IN THE MORE ORGANIC SOIL AND THE OTHER HAND TO ALLOW WATER TO FLOW VIA OLD ROOT CHANNELS.

To understand the dominant flows using the rationale in section 1.4 (for the Old Forest and Plantation sites), I it can be assumed that points having the highest *Kfs* and *φm* will have the greater macorporosity and may include greater preferential flow pathways, due to decomposition of root systems (Bengough, 2013). Overall, the median *Kfs* value is highest in the Plantation site, allowing a median of 20.25 mm/15 min of rainfall to enter the soil, whereas the median *Kfs* value allows only 8.55 mm/15 min of rainfall to enter the soil. During rainfall measurement the highest rainfall intensity recorded was 17.2 mm in 15 min, during the winter in the Old Forest site, which means that the Old Forest is likely to experience some infiltration excess overland flow, unlike the Plantation site (Figure4). However, the overall results are more complex than the dominant flow pathways suggested in the hydrological conceptual model in Figure 4.

The Old Forest has more significantly developed organic matter layers, where the organic soil and vegetation understory of bilberry, bearberry, heather and sphagnum are significantly deeper than the Plantation site (Figure 22). As shown in Figure 27, *Kfs* values for the Old Forest site is more heterogeneous than the Plantation site, because the range of *Kfs* values is larger in the Old Forest site (Table 3). The significantly greater *Kfs* values measured within the vegetated mounds in comparison to measurements taken in depressions in the Old Forest (Figure 29), suggests a “dual” system of infiltration rates, where the organic understory allows rainfall to enter the soil system rapidly, but then the more peaty depressions have finer pores, which allows water to infiltrate more slowly. Taking into account the range of *Kfs* enables an understanding of the full range of possible infiltration rates between the two sites.

The organic understory in the Old Forest also shows greater heterogeneity of soil water contents than the Plantation. For example Sensors 5 and 7 (Figure 19) show relatively large fluctuations of soil water contents. In particular, Sensor 5, which is placed within the pine roots of a ~300 year Scots pine tree, has a range of soil water content change from 0.4 to 1, suggesting that rapid sub-surface flow occurs within the pine roots during winter and also for a moment during the summer, triggered by low intensity, long duration rainfall. On the other hand, Sensor 8, which is installed in peat below a sphagnum mound, is constantly highly saturated, indicating the presence of an available supply of water, as Sphagnum needs a relatively constant supply of water (Hayward and Clymo, 1982). Sensors 5, 7 and 8 The soil water content measured by Sensors 5, 7 and 8 tend to lag behind rainfall events, suggesting that the vegetation and soil buffers rainfall infiltration for all these sensors. Sensor 6 (installed in sandy gravel) on the other hand is very responsive to rainfall (Figure 21), suggesting that rainfall infiltration rapidly infiltrates to the gravel layer.

In the plantation the soil water curves are more homogeneous, where for example Sensors 2 to 4, are located in course sand and gravel (Figure 16) and respond quickly to rainfall events and drain quickly (Figures 18 and 20). Fast draining soils mean that the soils are dominated by macropores, which have a lower ability to retain water. For all these locations infiltration rates are high, as also shown by the median *Kfs* value (and narrower range of *Kfs* values) in the Plantation. Sensor 1 (located in a peat depression) at the bottom of the slope does however remain almost saturated through the year, although it also responds to rainfall (Figure 18).

In answer to Hypothesis 1: It is to suggest that the forest root system creates macropores and increasing organic matter to optimise water flow and storage, when the gravel/sandy substrate below the forest (in this case moraine deposits) is highly permeable. The Old Forest however is a community of diversity where a combination of vegetation mounds, depressions and root systems develop a system of fast and slow infiltration rates. It is the dense undulating community of organic matter, blaeberry, bearberry, heather and sphagnum that creates storage and release of water, allowing a very stable system that does not simply allow infiltration, but also in the dense peat areas, water is stored and slowly percolates, when the peat is saturated.

4.2 INVESTIGATING HYPOTHESIS 2) SPRINGS DEVELOP WITHIN AND AROUND MATURE FORESTS BECAUSE THEIR ROOTING SYSTEMS INTERACT WITH THE SOILS IN SUCH A WAY AS TO FORM PERMANENT AND/OR EPHEMERAL PERCHED WATER TABLES

Using the positive and negative feedback loops for spring formation shown in Figure 5, we will focus on positive feedbacks, i.e. feedbacks that create springs. Figure 31 divides the positive feedback factors into two categories: Physical environment and water flows. As described in Section 2 and summarised in Figure 14, the physical environment within the Cairngorms creates perched water tables because of glacial processes, depositing morainic mixed permeable material on top a more impermeable till layer. Glacio fluvial processes also forms differing layers of permeability, depending on, for example ponding or slow moving water depositing finer materials, forming intermittent impermeable layers and creating localised perched water tables. Such a physical environment provides the conditions for perched water tables.

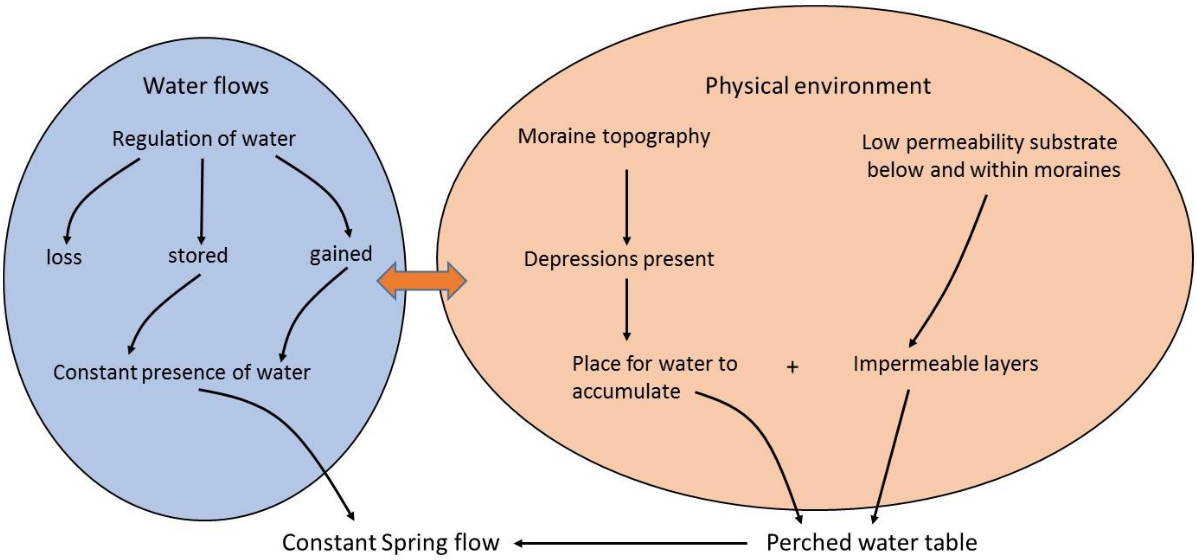


Figure 31) Positive feedback loops for spring formation

To ensure a constant spring flow, the environment needs to enable water accumulation for the storage of water and conditions that regulate water flow to ensure continual replenishment of water (Figure 31).

4.2.1 Water flows in the Plantation site.

The dense plantation canopy intercepts more rainfall than the Old Forest (Figure 22) and therefore reduces the amount of rainfall that enters the ground in the Plantation. It is striking to have a difference of 134 mm less of rainfall in the Plantation than the Old Forest, when this does not include the winter rainfall, because the datalogger failed to function in the Plantation during most of the winter in 2015 to 2016. This however is 15 percent less rainfall from the total measured in the Old forest, which is similar to interception recorded in Scots pine plantations in the Mediterranean (Llorens, et al. 1997). Therefore, there is a loss of water through interception, which reduces available water for springs to form.

What happens to this excess of water from rainfall that enters the soil in the Plantation site? According to the soil water content curves (Figure 18) the water infiltrates the soil relatively quickly as there is only a short lag between rainfall events and peak soil water contents and then the soil drains relatively quickly (Figures 18 and 20). Below the break of the slope, where the soil layer is thicker, soil moisture contents remain relatively high (Sensor 1 in Figures 18 and 20). This suggests that the gravel soils in the hillslope of the plantation site allow rainfall to infiltrate and drain towards the bottom of the slope, where the soil water enters the peat at the bottom of the slope, i.e. the bottom of the moraine depression (Figure 30). The high *Kfs* values (Figure 27) measured in the Plantation corroborate the relatively fast response of the soil water sensors in response to rainfall events. The significantly thinner organic soils and vegetation depth (Figure 23) in the Plantation infers that there will be less rainfall intercepted by understory vegetation and less storage of rainfall in the upper organic soil in comparison to the Old Forest. It is also interesting to note that overall the drainage channels have lower *Kfs* values, than the adjacent mounds, (Figure 29); this could facilitate surface water flow in drainage lines. These observations do not explain spring development in the moraine slope, but rather water flow is predominantly downslope towards the bottom of the moraine, creating an accumulation of water within the perched bog that seeps into the nearby river. The reason for the significantly thinner soils in the Plantation site in comparison to the Old forest, could be for a number of combined reasons, such as: 1) during the implementation of drainage and tree planting, the peat soils became disturbed and vulnerable to erosion by the increased amount of water flow through the newly installed drainage, 2) the loss of shrub canopy through the process of tree planting exposes the soil to erosion and as the plantation grows, the loss of understory biodiversity, causes the soils to become eroded particularly under high rainfall, 3) with increased infiltration rates, the soils are more highly drained, causing the water table to lower. The peat then becomes drier and oxidization of the peat occurs, lowering the depth of peat (Zanello, 1t al. 2011). More investigation needs to be done to understand why the peats are thinner in the plantation site.

Because the moraine soils are highly permeable, it is difficult to find evidence that tree roots have an effect within this system, because no difference was found in *Kfs* samples near trees or further away from them, tending to suggest that the moraine substrate is the dominant driver for rainfall infiltration. In a previous study, it was found that a 40 year old Scots pine plantation in gravel soils did not have significantly greater infiltration rates compared to an adjacent grass area on the same gravel soils (Archer, et al. 2013). More work is needed to be able to define the effect of tree roots in permeable soils.

The observations of the peat drying out and deep cracks forming in the peat during a period of little rain during October 2016 is an important observation, as the peat cracks create preferential flow, where water by-passes the peat matrix. This may cause flashy, large river flows, if heavy rainfall occurs after a period of drought in the Cairngorms.

4.2.2 Water flows in the Old Forest site

The greater capacity for the forest soils to retain water and the higher cumulative amount of rainfall (Figure 22) in the Old Forest, will cause higher soil water contents in the Old Forest soils in comparison to the Plantation site (Figures 18 and 19). The significantly greater vegetation depth creates greater rainfall interception and greater soil depths will increase rainfall storage in the Old Forest in comparison to the Plantation site (Figure 23). The significantly higher *Kfs* in vegetation mounds in comparison to depressions (Figure 29) shows that vegetation facilitates rainfall infiltration in the Old Forest site, but infiltration rates are lower in depressions. The soil moisture probes show a diverse range of response to rainfall (Figure 19), but there is no strong indication of increasing soil water content downslope, where for example, Sensor 8 which is upslope of the others (Figure 7), has consistently saturated soils, suggesting that there is a shallow supply of water upslope, to the other soil sensors (Figure 19). Overall the environment of the Old Forest site tends to gain and store water, which will facilitate constant spring flow within the moraine slopes. Even during the dry period in October 2016, when the peat soils were dry and cracking in the Plantation site, the peat soils in the Old Forest site remained relatively wet although the seepage within the Old Forest became dry and the spring below the site continued to flow.

Overall, the older mature Old Forest environment is one of diversity, where the undulating mixed understory of blaeberry, bearberry, heather and sphagnum species form a relatively thick layer above ground and below ground a dense layer of roots exists to at least 0.4 m, depending on the depth of organic soil material and permeability of substrate depth. To quantify specifically the effects of tree roots in this environment, requires a great deal of work, which is beyond the scope of this project, because the augering method did not penetrate the substrate deep enough to enable observation of deeper tree roots. Also, the conservation status of these rare old Scots pine trees and the surrounding environment prevents destructive digging to enable observation of the root system and to place instrumentations within and below the deeper root systems.

In answering hypothesis 2, it is important to question whether the two sites regulate water flow that facilitate a constant water supply for springs (as illustrated in Figure 31). As discussed in this section, the combination of a diverse understory canopy and deeper peat soils allows rainfall to be stored, which is slowly released into the sandy gravel substrate which drains to accumulate above finer more impermeable substrate to produce a spring within the moraine slope. The results in the Plantation site show the lack of understory vegetation and a propensity for water to infiltrate the soil and allow water to drain downslope, causing water to accumulate in the moraine depression.

4.3 FOREST MANAGEMENT AND WATER DISTRIBUTION

The observations and measurements at the two sites question the management of drainage in the Plantation site. Ploughing drainage lines into the fragile peat layer may decrease peat depth on the moraine slopes. As there are no records of peat depth before planting, it is difficult to know the impact of draining and planting areas in the Cairngorms. Deep ploughing may also disturb thin layers of low impermeable substrate, reducing areas for perched water tables to form and therefore reducing seepages and springs.

The drainage lines in the Plantation site successfully direct water towards the moraine depression. This raises the question: why do the majority of windblown trees occur at the bottom of moraine depressions (Figure 8)? According to Mickovski and Ennos (2002), the most important roots to provide anchorage are the tap and sinker roots. The growth of these roots may be repressed in waterlogged soils in the moraine depressions, suggesting that trees should not be planted in the waterlogged soils in moraine depressions. Certainly Scots pines grow well on the moraines as shown in the old Sots pine forests in the Rothiemurchus estate, where there are significantly more Scots pine trees growing on moraines than in their adjacent depressions (Figure 11). Vinke and Thiry (2008) observed Scots pine in Belgium to extract water from the water table during the summer and drought period, which could suggest that the old Scots pine in Rothiemurchus, may avoid water logging during the winter by their elevated morainic position and during the drier summer months they may extract water from the nearby moraine depressions. Further investigations of water dynamics is needed to understand the possible water logging of mature Scots pine and the impact this may have on forestry in the Cairngorms.

4.4 FORESTS AND FLOOD MANAGEMENT

The positive benefits of forests to attenuate flooding are through the greater water use by trees, the ‘sponge effect”, where i) the more organic soils absorb and store water, delaying water draining by sub-surface flows to streams and rivers and, ii) increased infiltration through root penetration into poorly draining soils and greater hydraulic roughness resisting overland flows in floodplains (Nesbit and Thomas 2006). However, investigations on the effect of trees on hydrology in Scotland suggests that the main driver of runoff generation is soil type, which is more significant than vegetation effects in wet northern headwater catchments (Geris et al. 2014). In terms of the Plantation site in this investigation, the fast response and low retention of highly permeable moraine soils are dominant factors allowing rainfall to infiltrate soils and the combination of drainage channels implemented before the planting of trees may have an overall greater impact on facilitating water downslope towards moraine depressions. To determine if the presence of roots in the Plantation site significantly increases water infiltration in such permeable soils, further investigation is needed.

In addition to this, the overall lower amount of rainfall reaching the ground in the Plantation, suggests that rainfall canopy interception does occur in the Plantation, reducing rainfall to enter the soil. The short duration of rainfall measurements in this study however could not provide the long-term data needed to record the less prevalent high rainfall intensity events that cause floods. Other studies in Scots pine plantations have observed decreased interception with increasing rainfall magnitudes (Llorens, et al. 1997). Therefore, high rainfall intensities in the Plantation site could still reach the soil. If such rainfall coincided with dry cracked peat soils (as observed in the Plantation site in October 2016), high intensity rainfall would enter streams relatively quickly to facilitate fast rising waters in the Cairngorms.

As discussed in Section 4.2.2 the Old Forest tends to act as a “sponge” to rainfall within the moraine slope, storing water. Kurbatov (1968) makes a distinction between forest peat, which he describes as being more aerated and similar to thick litter deposits, unlike peat in swampy anaerobic conditions, which remain saturated. For the soil water content to increase from 0.4 to 1 $m^3\ m^{-3}$ as measured in the forest peat (Sensor 5 in Figure 19), the soil must be composed of 60% air filled pores. The greater diversity of *Kfs* values measured in the Old Forest, allows for a system to partition water into stored and infiltrating water, this combination retains rainfall in the moraine slope and therefore slows down water entering streams at the bottom of the moraine depressions.

5 Conclusions

Following the results and discussion of this investigation, Figure 32, summarises the geological structure of the moraine system, locations of perched water tables and dominant water flow directions inferred by measured soil water contents and *Kfs* measurements within the Plantation and Old Forest sites. Figure 32, illustrates the necessary presence of the harder till layer to allow for possible perched water tables under the more permeable moraine substrate. Because of the glacial fluvial nature of moraine formation, ponding and compaction caused by retreating ice sheets can create lenses of fine, more impermeable layers to create localised areas of perched water tables within the moraine slopes.

Within the Plantation site, soils and vegetation are significantly shallower than in the Old Forest site and water flow is driven by the highly permeable moraine substrate and drainage lines implemented before tree planting, causing greater infiltration of rainfall downslope to the boggy moraine depressions, where streams flow. Overall the dense plantation canopy tends to intercept and reduce rainfall reaching the ground and during a dry period, the deeper peat soils toward the bottom of the moraine were observed to dry out and crack. However, as there is a lack of high intensity rainfall data in the Plantation site, it is not possible to conclude that the dense canopy also intercepts a high percentage of storm rainfall that may cause flooding. Further rainfall measurements are needed to understand rainfall interception in the Plantation site.

The large range of *Kfs* values from (0.00004 to 4.80 cm/min) in the Old Forest infers that the soils have the ability to retain (low *Kfs* values) and release water (high *Kfs* values) within the moraine slope. These extreme values have developed in the Old forest site, due to the diverse forest understory of sphagnum, blaeberry, heather and bearberry, where the vegetation maintains deeper peat soils and sandy gravel soils dominate the depressions. This causes a ‘dual’ system of water retention in soils below vegetation and water release in the sandy gravel substrate in depressions between vegetation mounds. Such a system allows storage of rainfall in the moraine slope, maintaining a constant supply of water to accumulate above finer more impermeable substrate producing springs within the moraine slope.

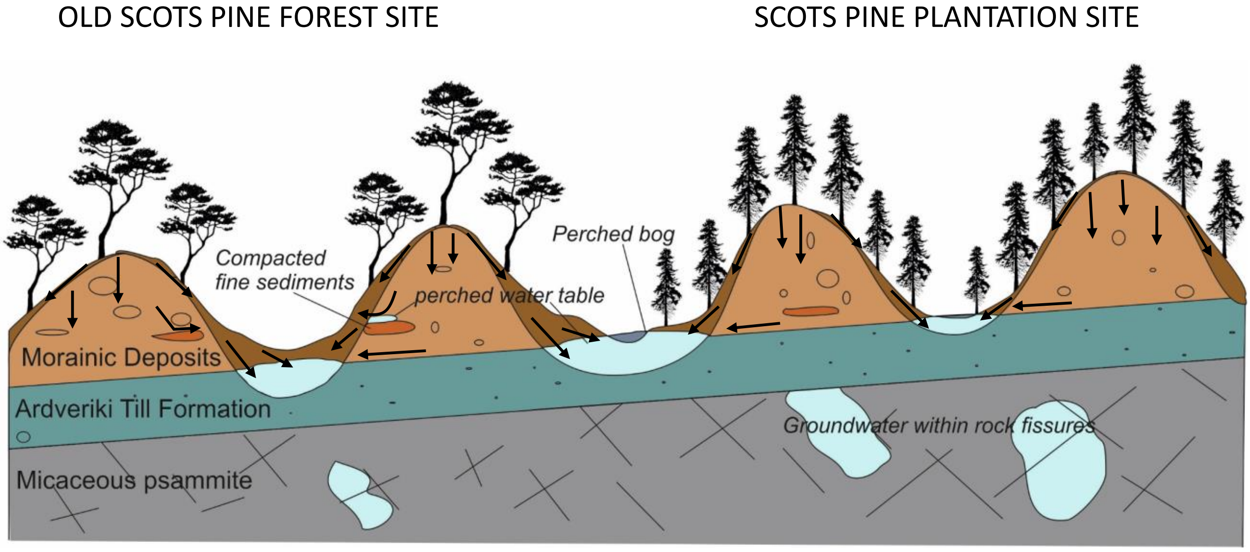


Figure 32) Arrows summarise water flow within the Old Forest and the Plantation sites.

In terms of the forest adjusting to its environment to form springs is not clear in this study. The large root system of the ~300 year old Scots pines are difficult to quantify when disturbance must remain at a minimum within the designated SSSI area, but this study has provided a good basis for furthering this work in the future.

The Old Forest site provides a rare opportunity to investigate a system where trees have been left to survive for over three hundred years and perhaps the more diverse system of open tree areas and dense understory may be a natural system to learn form in terms of developing natural flood management options to store and slow down high rainfall events within upland hill slope systems.

6 Recommendations and possible future work

- If trees are planted with the objective of reducing flooding, soil type and geology must be taken into account. In this study, the moraine soils are very permeable and implementing drainage before tree planting, could increase rainfall infiltration rates, which may induce local river flooding.
- Long-term rainfall measurements under plantation canopies are necessary to understand rainfall interception at low and high rainfall intensity events, for understanding the planting of trees for reducing flooding.
- Widely spaced trees, that are left to mature beyond 100 years and encourage a diverse understory, may be a better way to promote springs, ecosystem diversity, and greater water storage in the upland hill slopes as exemplified in the Old Forest site. This type of system may be a better way to mitigate flooding in the permeable moraine substrates in upland Scotland.
- In terms of understanding the development of springs in the Cairngorms, this study provides a preliminary understanding of the possible connections of geology and the glacial fluvial processes that created the moraine system and perched water tables in the moraine depressions and lenses of more impermeable layers within moraine hillslopes. More work is needed to understand the possible interconnectivity of perched water tables and the relationship of vegetation and springs.
- The significantly higher number of old Scots pine trees dominating the drier moraine slopes and crests rather than the boggy moraine depressions, could be a result of the Scots pine preference for drier soils or other reasons such as historical overgrazing. Understanding the reason for such spatial distributions may be important for improving forestry management. For example, to avoid the high number of wind-blown trees in moraine depressions, it may be more economical not to plant trees in waterlogged soils.
- The significantly shallower soil observed in the plantation questions whether the ploughing of drainage lines may cause a reduction in soil depth and a decrease of response time of rainfall throughflow to rivers. This needs further investigation for flood mitigation.
- Further work is needed to understand responses of rainfall to spring water and rivers in the Cairngorms. To avoid perturbation of the SSSI conservation sites in Rothiemurchus estate, water sampling for heavy isotopes and possibly tracer dyes from soil, springs and streams would be appropriate to avoid damage to Old Forest sites.
- To understand hydrological characteristics where water can be stored and released in different peat types, such as forest and bog peats, further investigation is needed to characterise these soils for flood management.

7 Continuing work

The available funds from the Scottish Forestry Trust for this project enabled the British Geological Survey to buy two pressure transducers to measure stream water levels and materials to install two stream gauging systems below the Plantation and Old Forest sites. This allows the possibility to continue monitoring the two sites to understand stream response time between the two forests.

Appendix 1

WORKSHOPS AND PRESENTATIONS

This work was presented 19th September 2015 at the Scottish National Heritage: **Making soils count - International Year of Soils Scotland 2015: Sharing Good Practice event** http://www.snh.gov.uk/news-and-events/events/event-details/?id=2839. This included a poster presentation and discussion about the work we have been doing.

We also presented this work to the public at the British Geological Survey Open Day 18th October 2015, which was hosted in Dynamic Earth, Edinburgh. Over 900 people came to visit the event.

ADDITIONAL INFORMATION

 Sensor 1	 Sensor 2	 Sensor 3	 Sensor 4
 Sensor 5	 Sensor 6	 Sensor 7	 Sensor 8

Figure 33) Positions of each of the soil moisture sensors

FINANCIAL STATEMENT

The project commenced in December 2014 and continued beyond the expected 21 months, because the dGPS (differential Geopositioning System) used in earlier field campaigns could not receive enough signal points in the plantation area. This caused difficulty to locate crests and depressions in the plantation site to provide understanding of hydrological flows. This however, was rectified using aerial stereo photogrammetry of the site to define topographical undulations, but caused a delay to finish writing the final report.

The funding confirmed from BGS was to pay for technical staff to undertake field work, analyse data, overhead charges and write reports: the total amount is: £18,948. The total requested amount from SFT is: £5,684. Of which £4,100 would be used to cover T&S for technical staff and transport costs to do the field work in the first 12 months and £1,584 is to cover equipment costs.

	December 2014 to March 2015	April 2015 to March 2016	April 2016 to end December 2016	Total
Field work T&S Equipment Laboratory analysis	£10,272 (BGS) £3100 (SFT) £1,5084 (SFT)	£3,767 (BGS) £1000 (SFT)	£5000 (BGS)	
Total cost BGS	£10,272	£8,767	£5,000	£ 18,948
Total cost SFT	£4685	£1000	No costs	£ 5,685
Yearly Total	£14,956	£9767		£ 24,724

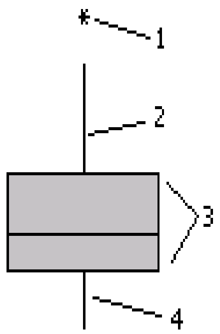
The final total costing for BGS (covering technical staff time) was £20,461 and the final total cost for T&S and equipment was £5,732, of which BGS will cover the excess amount. The financial accounts will be submitted with the final invoice.

Glossary

Alluvium: is loose unconsolidated soil or sediments which have been eroded and reshaped by water and redeposited in a non-marine setting.

ArcGIS: Geographical information System software, which is used to analyse spatial information

Boxplot:

	1 **Outlier (*)** − Observation that is beyond the upper or lower whisker 2 **Upper whisker** − Extends to the maximum data point within 1.5 box heights from the top of the box 3 **Interquartile range box** − Middle 50% of the data Top line−Q3 (third quartile). 75% of the data are less than or equal to this value. Middle line− Q2 (median). 50% of the data are less than or equal to this value. Bottom line − Q1 (first quartile). 25% of the data are less than or equal to this value. 4 **Lower whisker** − Extends to the minimum data point within 1.5 box heights from the bottom of the box

Glaciofluvio: Deposits transported from streams where much or all of their water is meltwater from glaciers.

Micaceous psammite: Micaceous Sandstone

Moraine: An accumulation of earth, gravel and cobbles carried and finally deposited by a glacier

Saturated hydraulic conductivity: is a quantitative measurement of a saturated soil's ability to transmit water when subject to a hydraulic gradient. It is an indication of the ease with which pores of a saturated soil permit water movement. The higher the value, the greater the ease of water movement within the soil matrix.

Spring: A place where water naturally flows to the surface of the ground and is the source of a stream (burn).

Till: unsorted glacial sediment, derived from erosion and entrainment of material by the moving ice of a glacier.

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